Marine Physical Laboratory

EM121 Sonar Calibration Experiment Using MPL's Phantom DS4 ROV

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Scripps Institution of Oceanography

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This report presents the results of a series of measurements carried out at sea in December 1995, to determine the acoustic source levels of a SIMRAD EM-121 multibeam echo-sounder installed aboard USNS SUMNER (TAGS-61). This was done by navigating a reference acoustic transducer, mounted on a Phantom DS4 ROV, below the hull of the ship. The work involved the collaborative efforts of personnel from the Naval Oceanographic Office (NAVOCEANO), the Naval Sea System Command (NAVSEA), SIMRAD, and the Marine Physical Laboratory (MPL). Personnel from the Naval Command Control and Ocean Surveillance Center (NRaD) in Warminster, PA, were involved also with acoustic data acquisition on the EM-121 hydrophone array, but these measurements are not discussed here. The measurements were taken around 25° 10'N, 77° 55'W at the northern end of the Tongue of the Ocean, in 2500 m of water depth.

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EM121 Sonar Calibration Experiment Using MPL's Phantom DS4 ROV

Christian de Moustier

1. INTRODUCTION

This report presents the results of a series of measurements carried out at sea in December 1995, to determine the acoustic source levels of a SIMRAD EM-121 multibeam echo-sounder installed aboard USNS SUMNER (TAGS-61). This was done by navigating a reference acoustic transducer, mounted on a Phantom DS4 ROV, below the hull of the ship. The work involved the collaborative efforts of personnel from the Naval Oceanographic Office (NAVOCEANO), the Naval Sea System Command (NAVSEA), SIMRAD, and the Marine Physical Laboratory (MPL). Personnel from the Naval Command Control and Ocean Surveillance Center (NRaD) in Warminster, PA, were involved also with acoustic data acquisition on the EM-121 hydrophone array, but these measurements are not discussed here.

The EM-121 operates at an acoustic frequency of 12 kHz and is designed for sounding over a 120° swath in water depths ranging from 10 m to 11 km. This system transmits and receives sound waves via two acoustic arrays mounted perpendicular to each other on the hull of the ship. The projector array consists of 58 hemicylindrical elements (460 mm radius, 151 mm length) mounted end to end along the ship's keel between frames 58 and 75. A broadside beam 1° wide in the fore-aft vertical plane is obtained when using all the elements of this array. Alternately, the system can produce a 2° beam using only 28 elements, or a 4° beam using 14 elements. The source level of the full array is specified at 240 dB re 1 μPa at 1m.

The hydrophone array consists of 128 hydrophone staves, each 540 mm long and spaced 58 mm apart, mounted athwartships in a V configuration at about frame 54. The sides of the V are inclined 10° from horizontal on either side of the keel.

To obtain reliable source level estimates, measurements should be made in the far-field of the acoustic arrays. To first order, the distance from the array face to the far-field can be approximated by the ratio of the square of the array length to the acoustic wavelength. Assuming a sound speed of 1500 m/s the acoustic wavelength at 12 kHz is 125 mm. For the projector array in its various aperture modes, this yields the following far-field distances:

627 m in 1° mode unshaded
154 m in 2° mode unshaded
41 m in 4° mode unshaded

For the hydrophone array, the far-field for one side of the V (aperture of ~3712 mm) is approximately 110 m in the unshaded mode.

Measurements were made at three different depths: 400 m, 200 m and 100 m.

The measurements were taken around 25° 10'N, 77° 55'W at the northern end of the Tongue of the Ocean, in 2500 m of water depth. Weather conditions were not optimum for this

type of work as winds speeds averaged 25 knots with gusts above 30 knots, the sea state ranged from 4 to 5, and there was a surface current of about 1 knot.

In the following sections we describe the hardware configuration and the measurement geometry (Section 2), we outline the data reduction steps and present the processed results (Section 3), and we conclude this report with recommendations for future measurements of this type (Section 4).

2. MEASUREMENT CONFIGURATION

2.1 PHANTOM DS4 ROV

The Phantom DS4 ROV is a positively buoyant vehicle propelled by 4 horizontal thrusters and 2 dihedral thrusters providing 100 pounds of forward thrust and 30 pounds of lateral and vertical thrust. It is deployed at the end of 600 m of slightly positively buoyant umbilical cable containing multiple electrical conductors.

Figure 1 shows a front and rear view of the ROV to which we have added a reference 12 kHz acoustic transducer (ITC-1007) and a Paro-Scientific pressure gauge. Two glass sphere in yellow plastic covers were added to maintain the righting moment of the vehicle and counterbalance the added mass of the 12 kHz transducer. This transducer is mounted on a fiberglass pole extending about 1m forward of the crash frame of the ROV to avoid, as much as possible, interferences from sound reflecting off the ROV body. The ROV is navigated with a Trackpoint II ultrashort baseline system manufactured by ORE International. ROV position data are referred to the Trackpoint II transducer seen in Figure 1 (rear view).

To reduce the drag of the umbilical cable during ROV operations at depth, we forced the umbilical to reach a prescribed depth by attaching it with plastic fasteners (tie-wraps) along a CTD cable paid out the starboard A-frame and held down by the weight stack of a piston corer. We left about 100 m of umbilical cable free between the ROV and the weight stack. When operating in water depths of less than 50 m, we made the free umbilical negatively buoyant along a 20 m span closest to the depressor weight by taping shackles every 2 m or so along that section of umbilical cable. This helped insure that the umbilical would not float up into the ship's propellers during shallow runs.

2.2 MEASUREMENT GEOMETRY

The measurement geometry is outlined in Figure 2 where three reference frames are depicted:

(1) the main reference frame whose origin (O) is at the center of the EM-121 projector array. The x axis points athwartships and is positive on starboard. The y axis is aligned with the ship's keel and is positive forward. The z axis is positive down.

(2) the Trackpoint II beacon reference frame with the same axis orientation as the main frame, but with the origin (O_T) translated by (x_{off}, y_{off}, z_A) from the main reference (O).

(3) the Trackpoint II transducer reference frame on the ROV with origin (O_r) and the same axis

orientation as the other two frames.

The position of the ROV is reported by the Trackpoint II system as a slant range *SR* in the beacon reference frame, a depth z referenced to the sea surface, and horizontal distances (x, y) as well as a bearing angle in the main reference frame. Note that the bearing angle θ shown in Figure 2 is the bearing angle actually measured by the system. Corrections are applied to transfer this measured bearing to the main reference frame before logging. The slant range *SR* reported by the Trackpoint II system is the one-way travel time from the Trackpoint II transducer to the beacon multiplied by the sound speed entered in the system. During the measurements, we used the harmonic mean sound speed at 100 m depth: 1538 m/s, taken from a CTD cast at the beginning of the measurement series and plotted as a sound speed profile in Figure 3. Because a single sound speed value was used at all depths, one of the data reduction steps consists in correcting the slant range to the harmonic mean sound speed for the actual measurement depth.

In this report, we are concerned with the ranges and bearings between the EM-121 projector array and the 12 kHz reference transducer mounted in front of the ROV. To this end, the position of the 12 kHz reference transducer in the main reference frame is computed via a rotation in the ROV reference frame (O_r) to account for ROV heading, and a translation from the Trackpoint II beacon reference frame (O_T) to the main reference frame (O) (Fig. 2).

Offsets between the EM-121 projector and hydrophone arrays and the Trackpoint II beacon are shown in Figure 4 and summarized along with all the other offsets in Table 1.

Main Reference Frame			
xA = 0	yA = 0	zA = 1.57 m	1° mode
xA = 0	yA = 2.26 m	zA = 1.57 m	2° mode
xA = 0	yA = 3.32 m	zA = 1.57 m	4° mode
Trackpoint II Beacon Reference Frame			
xoff = 8.89 m	yoff = 26.8 m	zoff = 7.74 m	
ROV Reference Frame			
x12k = 0.24 m	y12k = 2.06 m	z12k = 0.2 m	

Table 1. Offsets between reference frames.

3. DATA ANALYSIS AND RESULTS

3.1 DATA REDUCTION

Two types of measurements were made: (1) source level measurements during which the ROV transited along the fore-aft axis of the ship, and (2) athwartships beam pattern measurements during which the ROV followed an arc of circle at a prescribed radial distance from the ship. In all cases, the data reduction consisted of determining the (x,y,z) coordinates of the 12 kHz reference transducer in the main reference frame, computing the corresponding distance as

$$R = \sqrt{x^2 + y^2 + z^2}$$

and computing the sound pressure level received by subtracting the the 12 kHz reference transducer sensitivity from the rms voltage measured and adding and the one-way transmission loss (spherical spreading + absorption):

$$SPL = 20\log_{10}(R) + \alpha R - sensitivity + 20\log_{10}(Vrms)\ \ dB\ \ re\ 1\mu Pa\ \ @\ 1m.$$

with α = 1.1 dB/km, and sensitivity = -194.6 dB re 1V/ μPa.

The source level, the sensitivity and the beam patterns of the 12 kHz reference transducer have been measured at the Navy's TRANSDEC facility in San Diego, and the corresponding values are plotted in Figures 5 and 6. These plots show that, contrary to the manufacturer's advertized acoustic properties of the ITC-1007 transducer, it does not have a uniform beam pattern in the upper hemisphere when operated at 12 kHz. Note that the radiation pattern in the lower hemisphere is distorted by the mounting hardware used to secure the transducer to the ROV. In Figure 5, the ripple of ±0.5 dB seen within ±30° of zenith sets the limit of accuracy on the acoustic measurements taken along the ship's keel for EM-121 projector beam patterns in the fore-aft direction. The ripple is somewhat larger (±1 dB) outside of this sector, with increases of about 1 dB around 50° from zenith above the value at zenith. These increases are seen most prominently in the transmit beam pattern shown in Figure 6. The 12 kHz beam pattern provided by ITC for this transducer in a free field is shown in Figure 7 for reference.

The rms voltage was measured by digitizing at 48 kHz the 12 kHz pulse transmitted by the EM-121 and received on a direct path by the ITC-1007 transducer, and by retaining every other pair of samples as the quadrature components (I,Q) of the received signal. The data acquisition software computed the magnitude squared $(I^2 + Q^2)$ of the received digitized waveform, and computed an estimate of the steady-state voltage of the pulse by averaging instantaneous magnitude squared values that lie within 3 dB of the peak value. The rms voltage is then obtained by:

$$Vrms = [\frac{1}{2N}\sum_{i=1}^{N}(I^2+Q^2)_i]^{1/2}$$

3.2 RESULTS

The first set of acoustic measurements were taken at three different depths: 400 m, 200 m and 100 m, with the ROV transiting forward and backward along the ship's keel axis to sample the transmit beam pattern in the fore-aft direction. Plots of sound pressure levels vs fore-aft angle are shown in Figures 8-31. Most of these plots contain data from two opposing passes at the prescribed depth and EM-121 projector settings. In some cases a near perfect match is obtained between two such passes (e.g. Figs. 10,15,16,25), but for the most part, noise in the navigation data produces small discrepancies and one must consider the overall picture. Source levels in the various modes of EM-121 transmission are estimated by finding the maximum value in each beam pattern sequence and the results are reported in Table 2.

In the 4° mode, results are consistent at all depths with the manufacturer's specifications which call for 228 dB re 1 μPa @ 1m in the unshaded mode, and 225 dB re 1 μPa @ 1m in the shaded, full power mode. In all cases, measurements of the 4° beam were taken well into the far-field of the active segment of the projector array.

In the 2° mode, results of measurements taken at depths of 400 m and 200 m are also consistent with the manufacturer's specifications of 234 dB re 1 μPa @ 1m in the unshaded mode and 231 dB re 1 μPa @ 1m in the shaded, full power mode. Measurements made at 100 m depth

are self consistent but about 1 dB lower than expected, most likely because they were taken in the near-field of the active segment of the projector array.

In the 1° mode, measurements are in the near-field of the projector array when it is activated in the unshaded mode, so a -1 dB discrepancy from the manufacturer's specification of 240 dB re 1 μPa @1m is reasonable. In the 1° shaded, full power mode at 400 m depth, the far-field of the array is approximately that of the equivalent aperture for a 1° beam at 12 kHz (about 430 m), so the measurements should be, and is, close to the specified value of 237 dB re 1 μPa @ 1m.

Because of noise in the navigation data, sidelobe levels are not clearly defined in several of the beam patterns. However, unshaded patterns have sidelobes 12-15 dB below the main lobe, and shaded patterns have sidelobes 23-25 dB below the main lobe.

4° MODE					
depth	unshaded	full	-6dB	-12dB	-18dB
m	dB re 1 μPa @1m				
100	227.6	223.5	218.2	211.8	205.7
200	227.9	223.8			
400	227.5	224.2			
2° MODE					
depth	unshaded	full	-6dB	-12dB	-18dB
m	dB re 1 μPa @1m				
100	232.2	228.8	223	216.8	210.8
200	233.4	229.6	224.1		
400	234.0	230.7			
1° MODE					
depth	unshaded	full			
m	dB re 1 μPa @1m				
100		233.1			
400	239.0	236.9			

For the second set of acoustic measurements, the ROV was navigated along an arc of 100 m radius in the athwartships plane in order to sample the athwartships transmit beam pattern. This was done in the unshaded 4° mode only. However, due to a misunderstanding on the position of the center of the array segment used for the 4° transmit mode, in 2 out of 3 runs, measurements were taken in an athwartships plane going through the center of the entire projector array, that is 3.3 m to far aft for the 4° transmit mode. Unfortunately at a radial distance of 100 m, 3.5 m of fore-aft offset corresponds to a 2° offset, placing the measurement plane at the -3dB point on the 4° beam pattern. Therefore, results of these measurements are not reliable and only the general trend of the radiation pattern should be considered.

The sound pressure levels measured along the arcs swung to port and starboard are consistent with the source level measurements presented above. Figures 32 and 33 include measurements taken every degree along the arc while the ROV was within the 3 dB beamwidth of the beam in the fore-aft direction. The increase in sound pressure near -40° (port side) and +50° (starboard side) over that measured near 0° is most likely due to the 1 dB rise in the beam pattern of the reference ITC-1007 transducer in these angular sectors.

4. CONCLUSIONS

The source level measurements presented in this report are consistent with the manufacturer's specifications whenever the measurements were made in the far-field of the projector array. The athwartships radiation patterns were not measured appropriately to draw conclusions.

Many of the difficulties encountered while making the measurements had to do with the unfavorable weather conditions that prevailed throughout. Although the ship's crew did a remarkable job of keeping the ship on a steady heading and of minimizing the drift rate, the ROV is underpowered for such weather conditions. This explains also why measurements taken along the ship's keel while transiting from bow to stern are often better navigated and more stable than those on reciprocal headings.

Judging from the noise level found in the ROV navigation data, several interfering acoustic paths were present around the Trackpoint II beacon, mostly due to reflections from the ship's hull. In the future this can be alleviated by lengthening the pipe used to deploy the beacon, thus increasing the distance between the beacon and the ship's hull.

Lastly, a reference 12 kHz transducer with a more uniform beam pattern in the upper hemisphere should be used to refine the acoustic measurements. This might be done with an ITC-1001 which has a similar sensitivity but is much less efficient as a source.

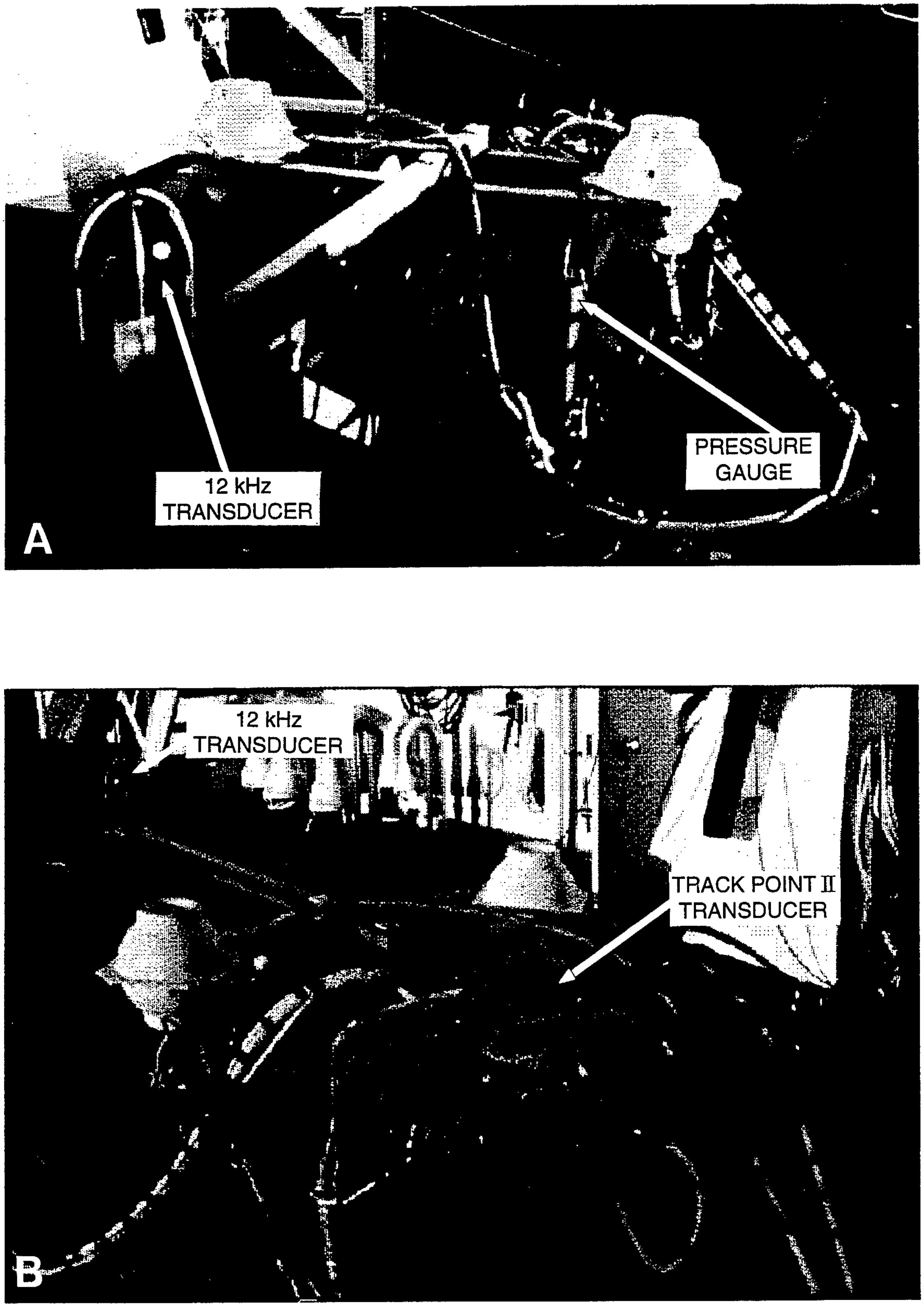


Figure 1. Phantom DS4 fitted with 12 kHz calibration transducer
A) front view and B) rear view.

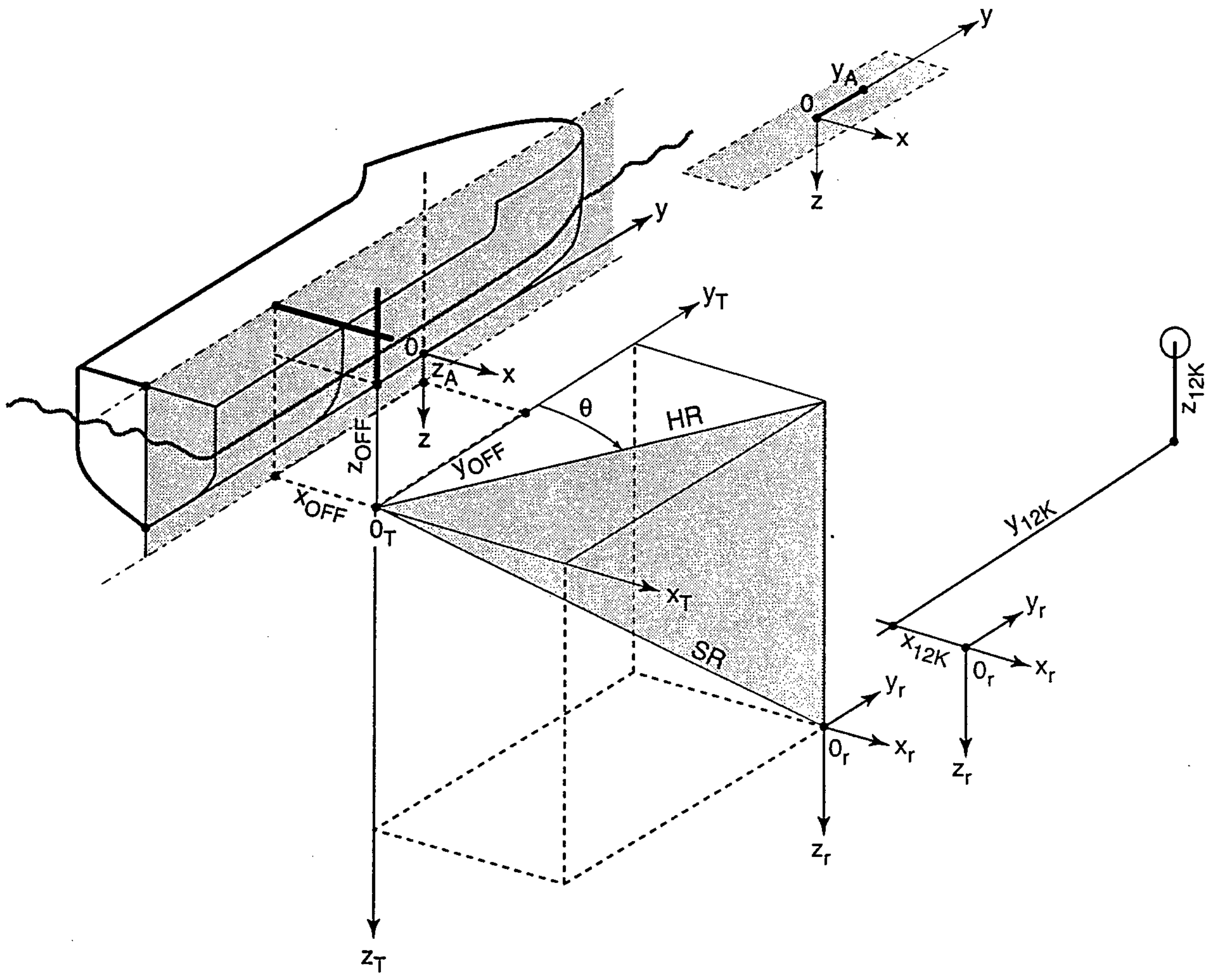


Figure 2. Geometry of Measurement

ALL DIMENSIONS IN METERS
EXCEPT WHERE NOTED

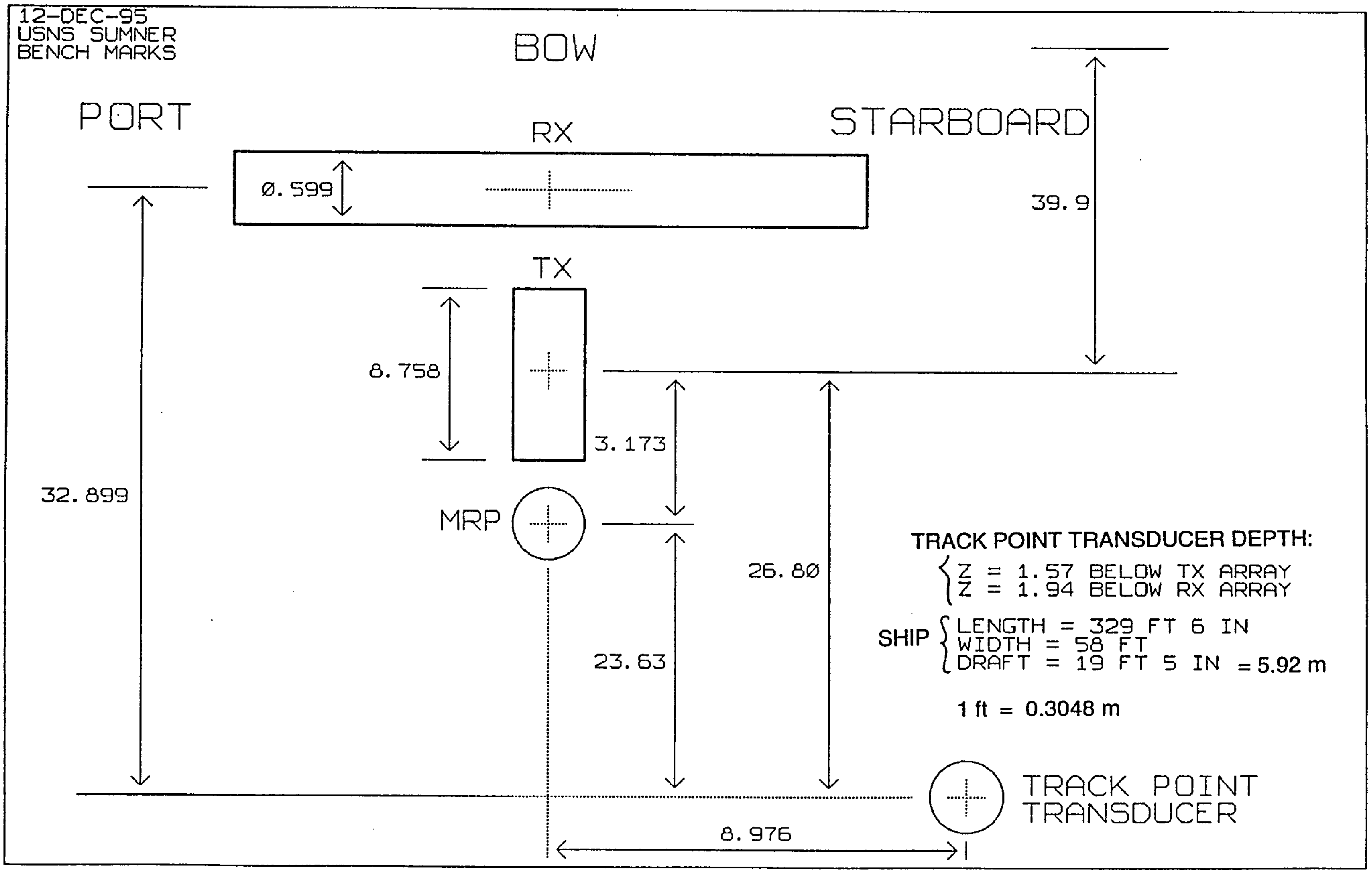


Figure 3

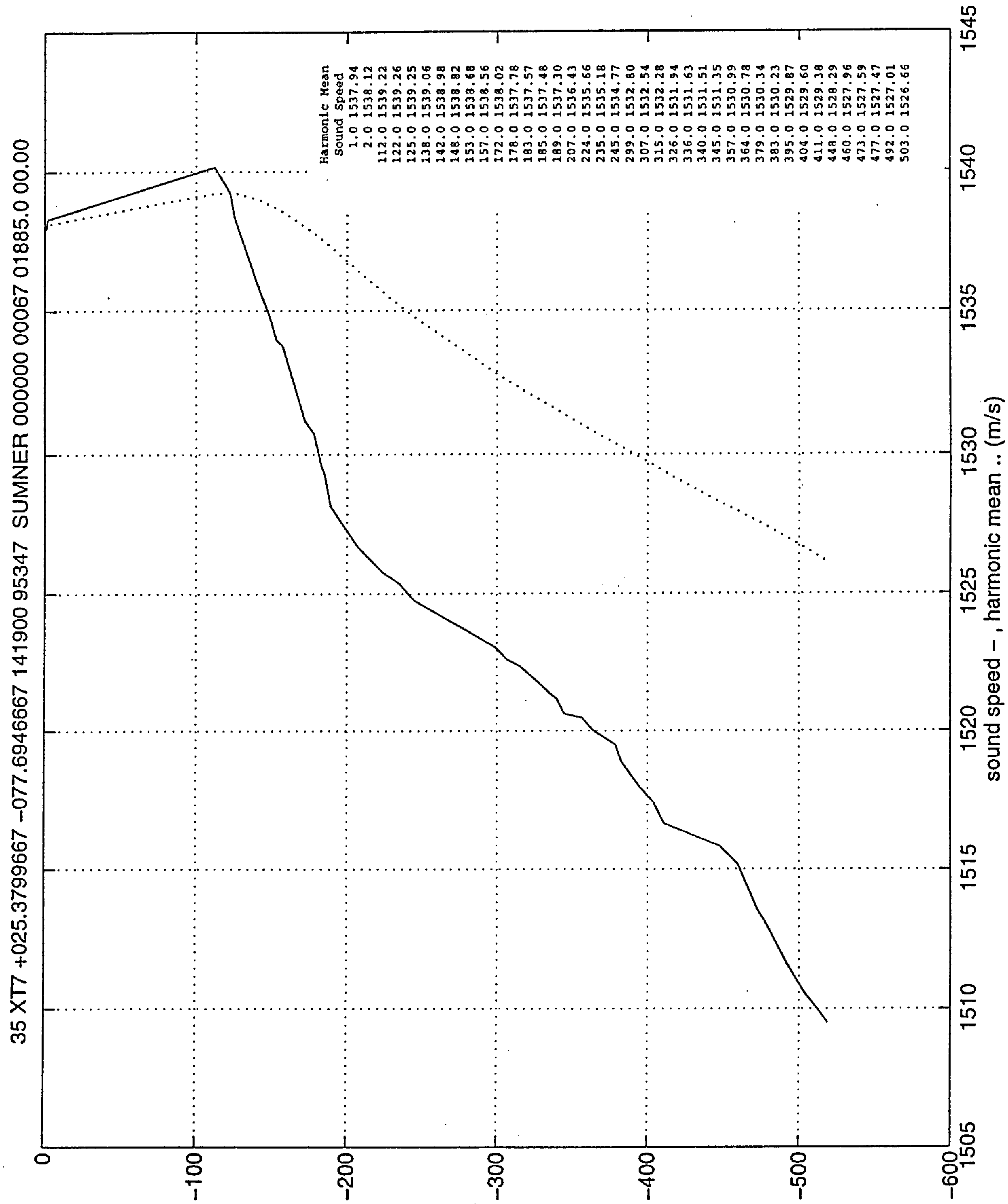

35 XT7 +025.3799667 −077.6946667 141900 95347 SUMNER 000000 00067 01885.0 00.00
depth (m)
0
-100
-200
-300
-400
-500
-600
sound speed – , harmonic mean .. (m/s)
1505
1510
1515
1520
1525
1530
1535
1540
1545
Harmonic Mean
Sound Speed
1.0 1537.94
2.0 1538.12
112.0 1539.22
122.0 1539.26
125.0 1539.25
138.0 1539.06
142.0 1538.98
148.0 1538.82
153.0 1538.68
157.0 1538.56
172.0 1538.02
178.0 1537.78
183.0 1537.57
185.0 1537.48
189.0 1537.30
207.0 1536.43
224.0 1535.66
235.0 1535.18
245.0 1534.77
299.0 1532.80
307.0 1532.54
315.0 1532.28
326.0 1531.94
336.0 1531.63
340.0 1531.51
345.0 1531.35
357.0 1530.99
364.0 1530.78
379.0 1530.34
383.0 1530.23
395.0 1529.87
404.0 1529.60
411.0 1529.38
448.0 1528.29
460.0 1527.96
473.0 1527.59
477.0 1527.47
492.0 1527.01
503.0 1526.66

Figure 4

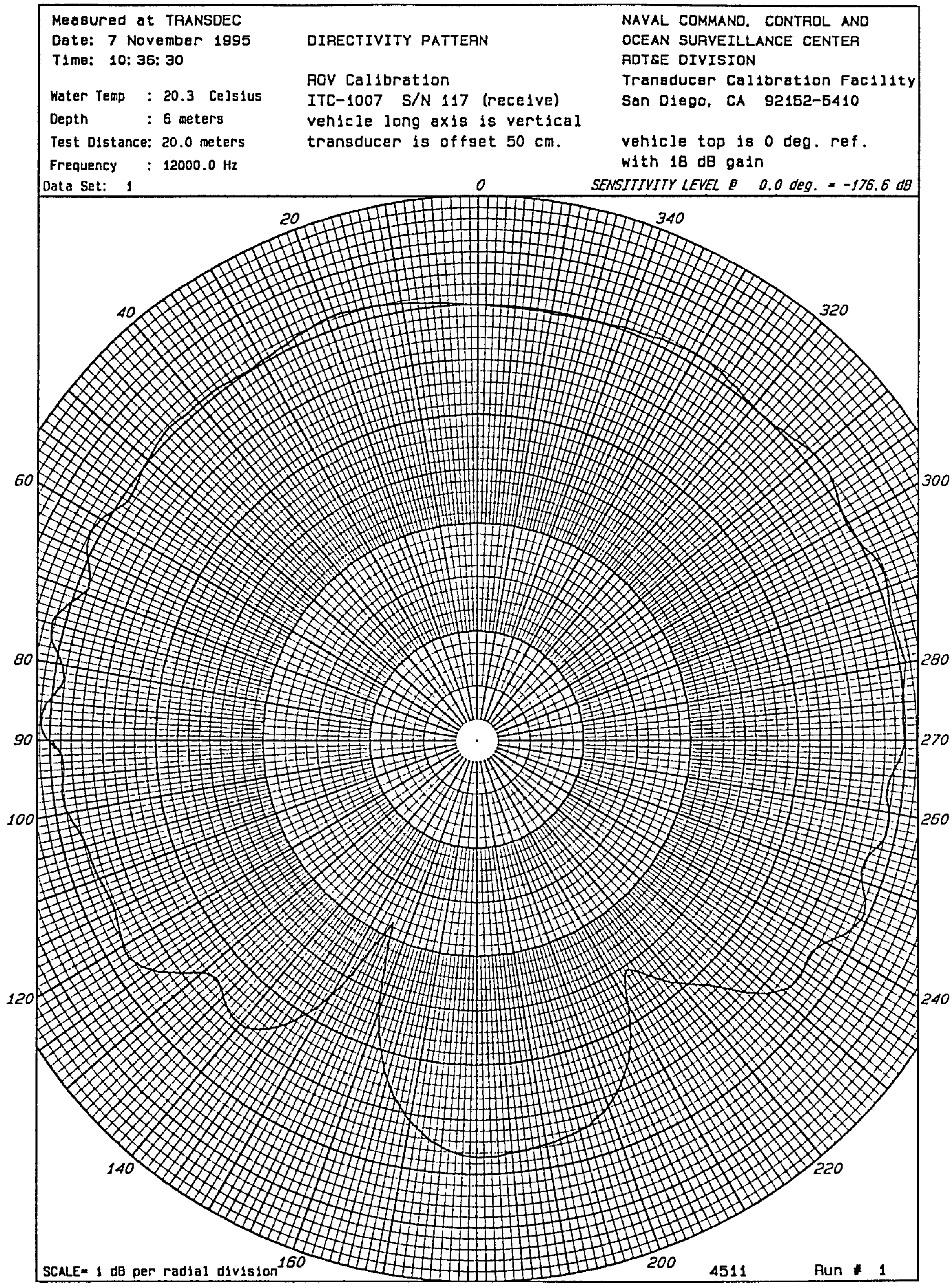

Measured at TRANSDEC
Date: 7 November 1995
Time: 10:36:30
Water Temp : 20.3 Celsius
Depth : 6 meters
Test Distance: 20.0 meters
Frequency : 12000.0 Hz
Data Set: 1
DIRECTIVITY PATTERN
ROV Calibration
ITC-1007 S/N 117 (receive)
vehicle long axis is vertical
transducer is offset 50 cm.
NAVAL COMMAND, CONTROL AND
OCEAN SURVEILLANCE CENTER
RDT&E DIVISION
Transducer Calibration Facility
San Diego, CA 92152-5410
vehicle top is 0 deg. ref.
with 18 dB gain
SENSITIVITY LEVEL @ 0.0 deg. = -176.6 dB
0
20
340
40
320
60
300
80
280
90
270
100
260
120
240
140
220
160
200
SCALE= 1 dB per radial division
4511
Run # 1

Figure 5

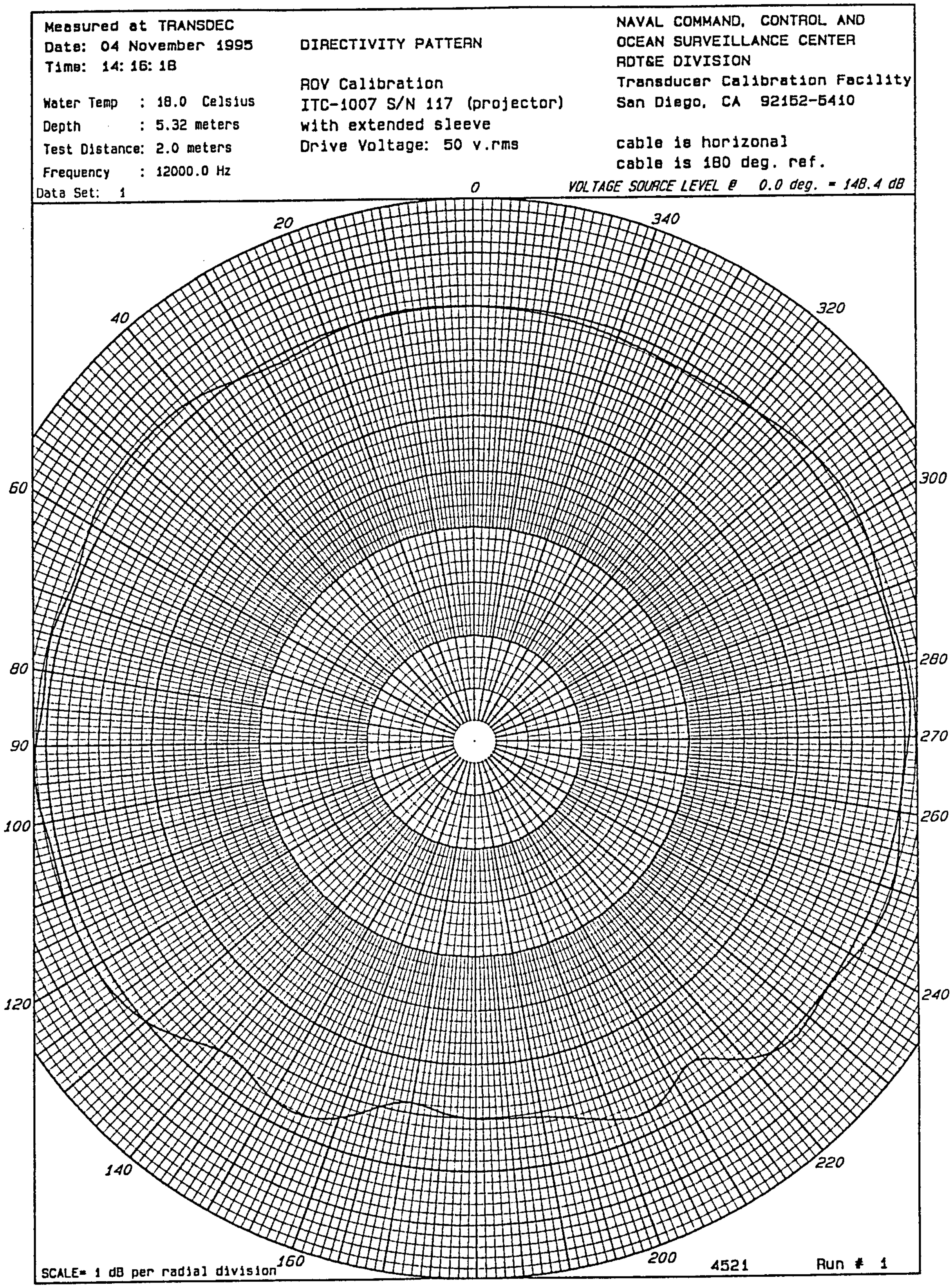

Measured at TRANSDEC
Date: 04 November 1995
Time: 14: 16: 18
Water Temp : 18.0 Celsius
Depth : 5.32 meters
Test Distance: 2.0 meters
Frequency : 12000.0 Hz
Data Set: 1
DIRECTIVITY PATTERN
ROV Calibration
ITC-1007 S/N 117 (projector)
with extended sleeve
Drive Voltage: 50 v.rms
NAVAL COMMAND, CONTROL AND
OCEAN SURVEILLANCE CENTER
RDT&E DIVISION
Transducer Calibration Facility
San Diego, CA 92152-5410
cable is horizonal
cable is 180 deg. ref.
VOLTAGE SOURCE LEVEL @ 0.0 deg. = 148.4 dB
0
20
340
40
320
60
300
80
280
90
270
100
260
120
240
140
220
160
200
SCALE= 1 dB per radial division
4521
Run # 1

Figure 6

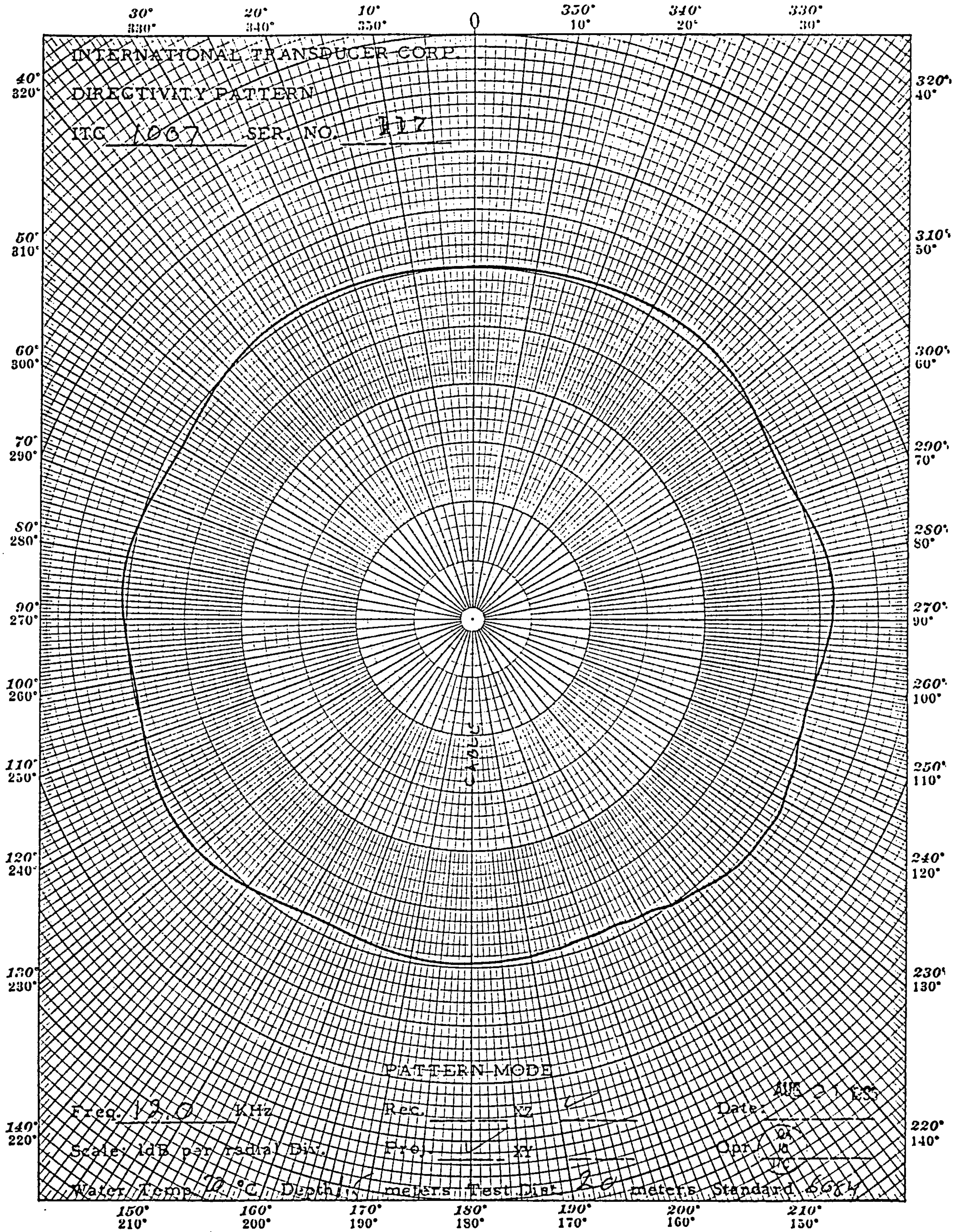

INTERNATIONAL TRANSDUCER CORP.
DIRECTIVITY PATTERN
ITC
SER. NO.
CABLE
PATTERN MODE
Freq.
KHz
Rec.
XZ
Date
Scale: 1dB per radial Div.
Pro.
XY
Opr.
Water Temp
°C
Depth
meters
Test Dist
meters
Standard

Figure 7

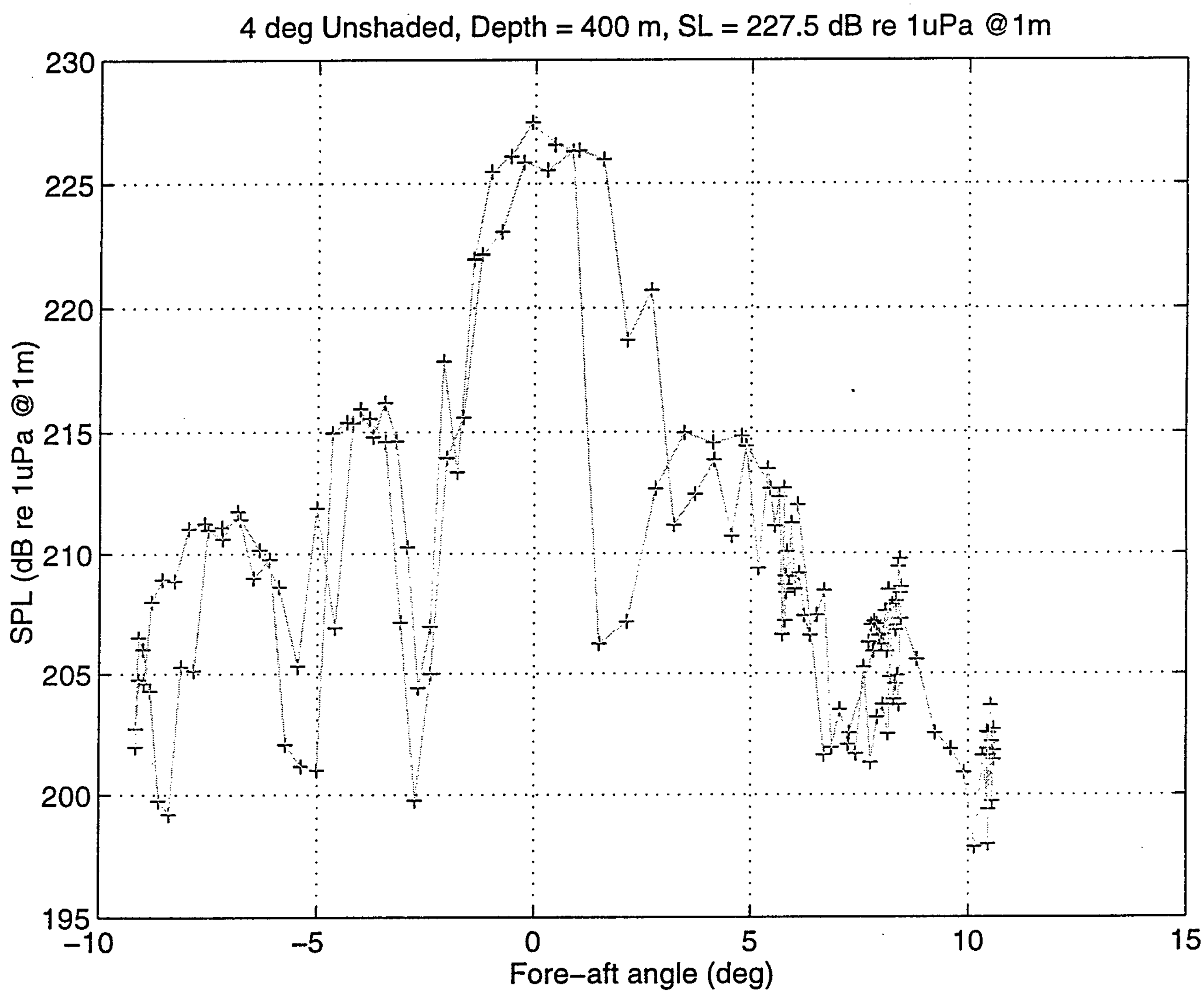

4 deg Unshaded, Depth = 400 m, SL = 227.5 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore–aft angle (deg)
230
225
220
215
210
205
200
195
−10
−5
0
5
10
15

Figure 8

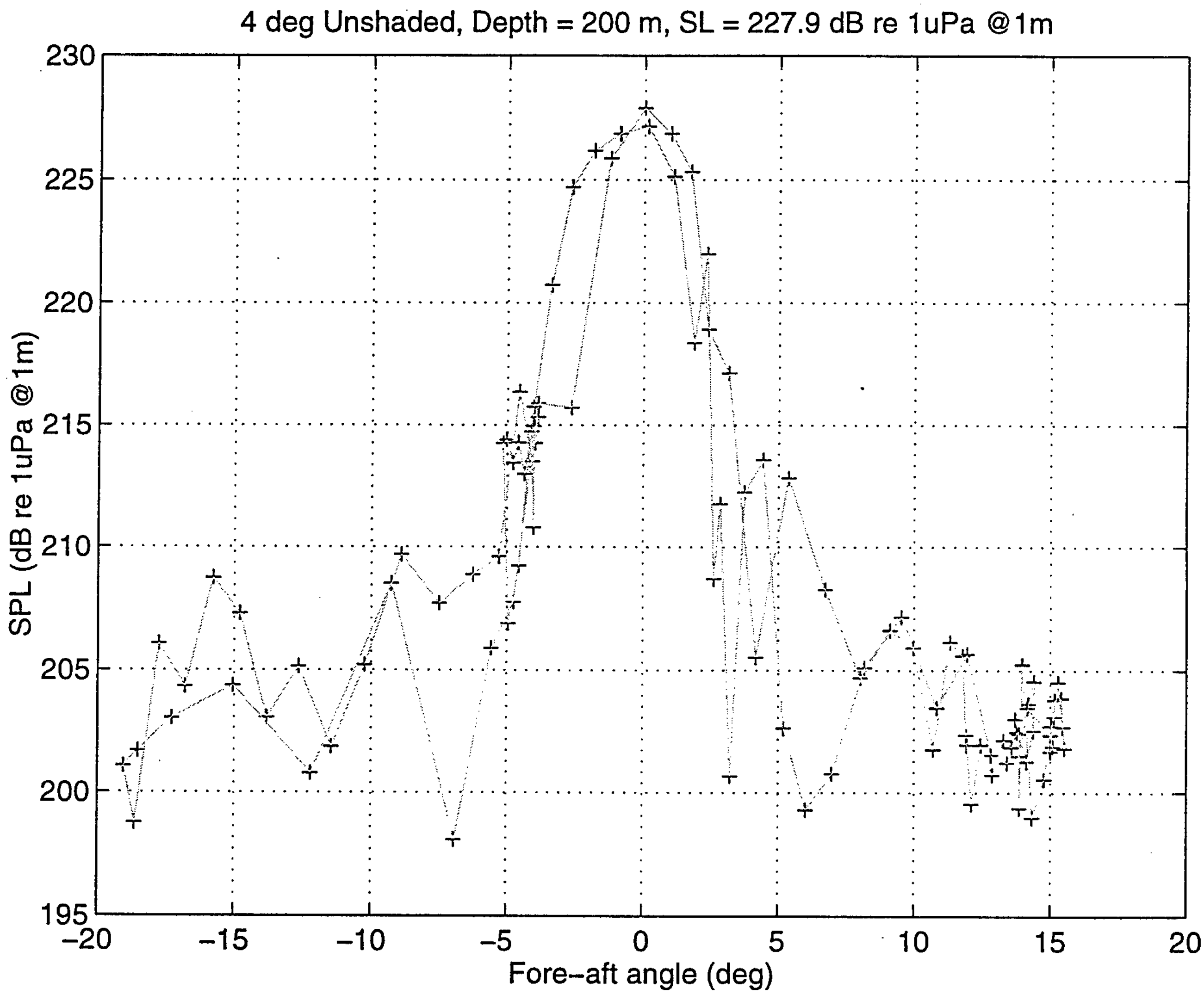

4 deg Unshaded, Depth = 200 m, SL = 227.9 dB re 1uPa @1m
230
225
220
215
210
205
200
195
SPL (dB re 1uPa @1m)
−20
−15
−10
−5
0
5
10
15
20
Fore−aft angle (deg)

Figure 9

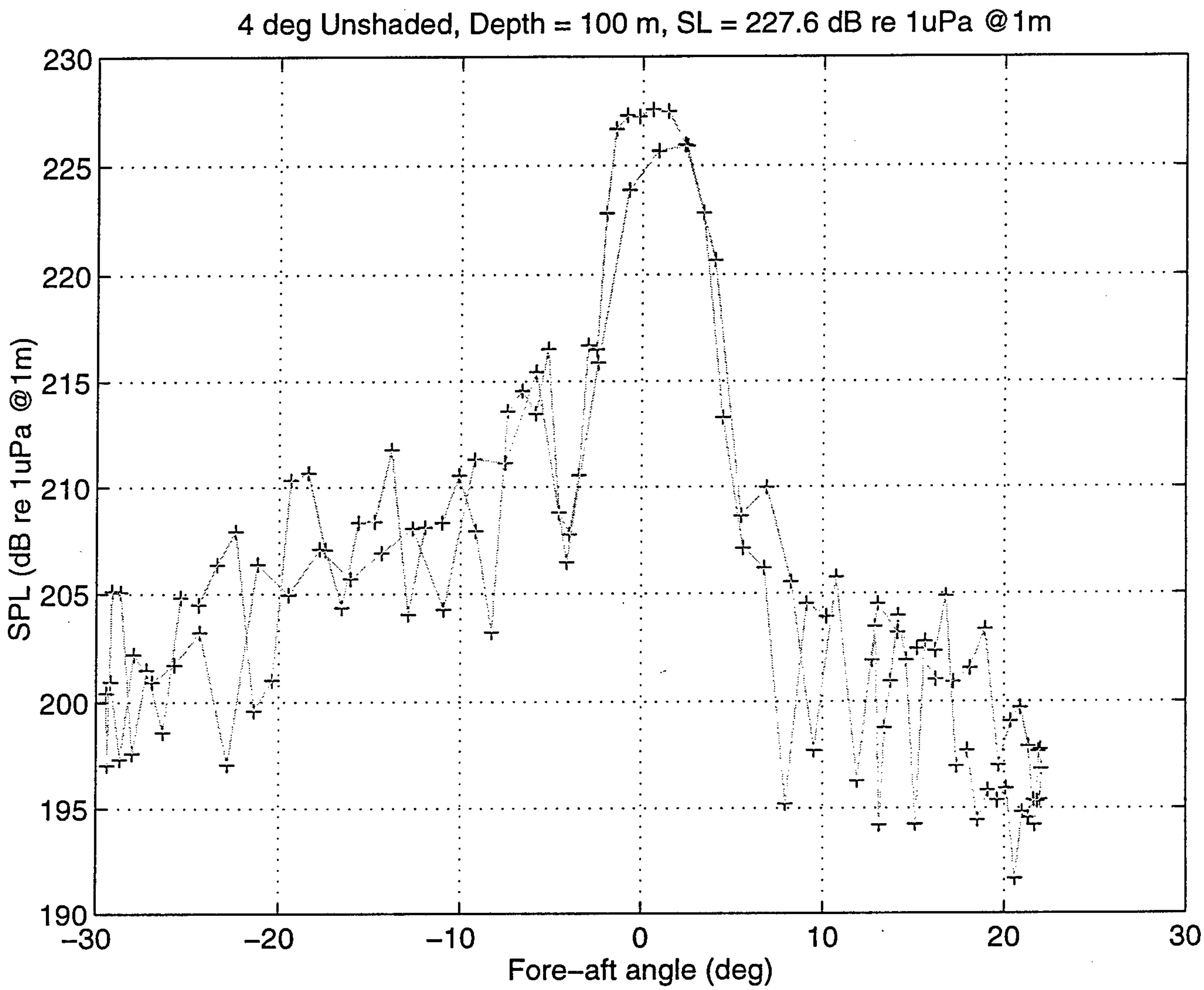

4 deg Unshaded, Depth = 100 m, SL = 227.6 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore–aft angle (deg)
230
225
220
215
210
205
200
195
190
−30
−20
−10
0
10
20
30

Figure 10

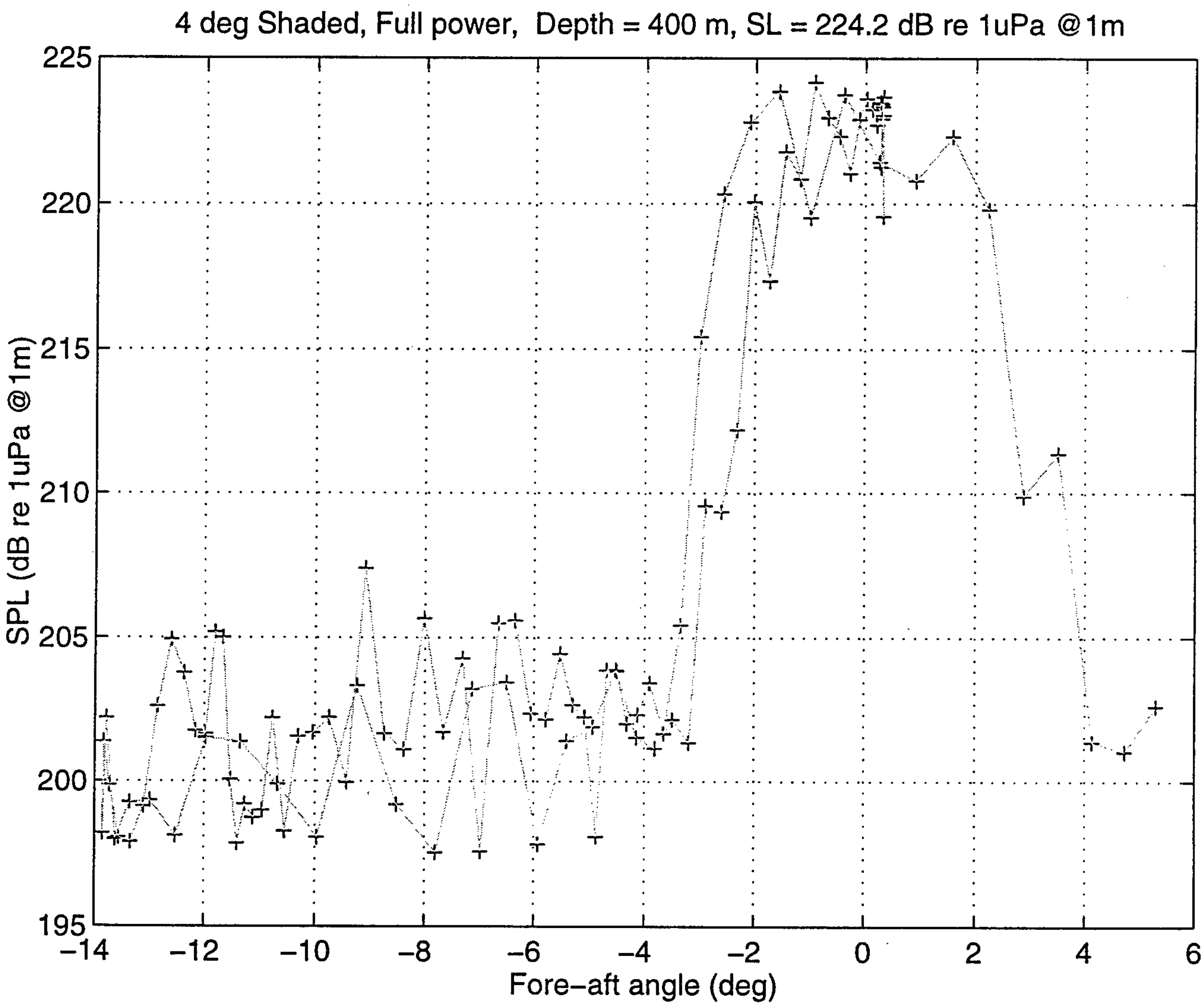

4 deg Shaded, Full power, Depth = 400 m, SL = 224.2 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
225
220
215
210
205
200
195
−14
−12
−10
−8
−6
−4
−2
0
2
4
6
Fore−aft angle (deg)

Figure 11

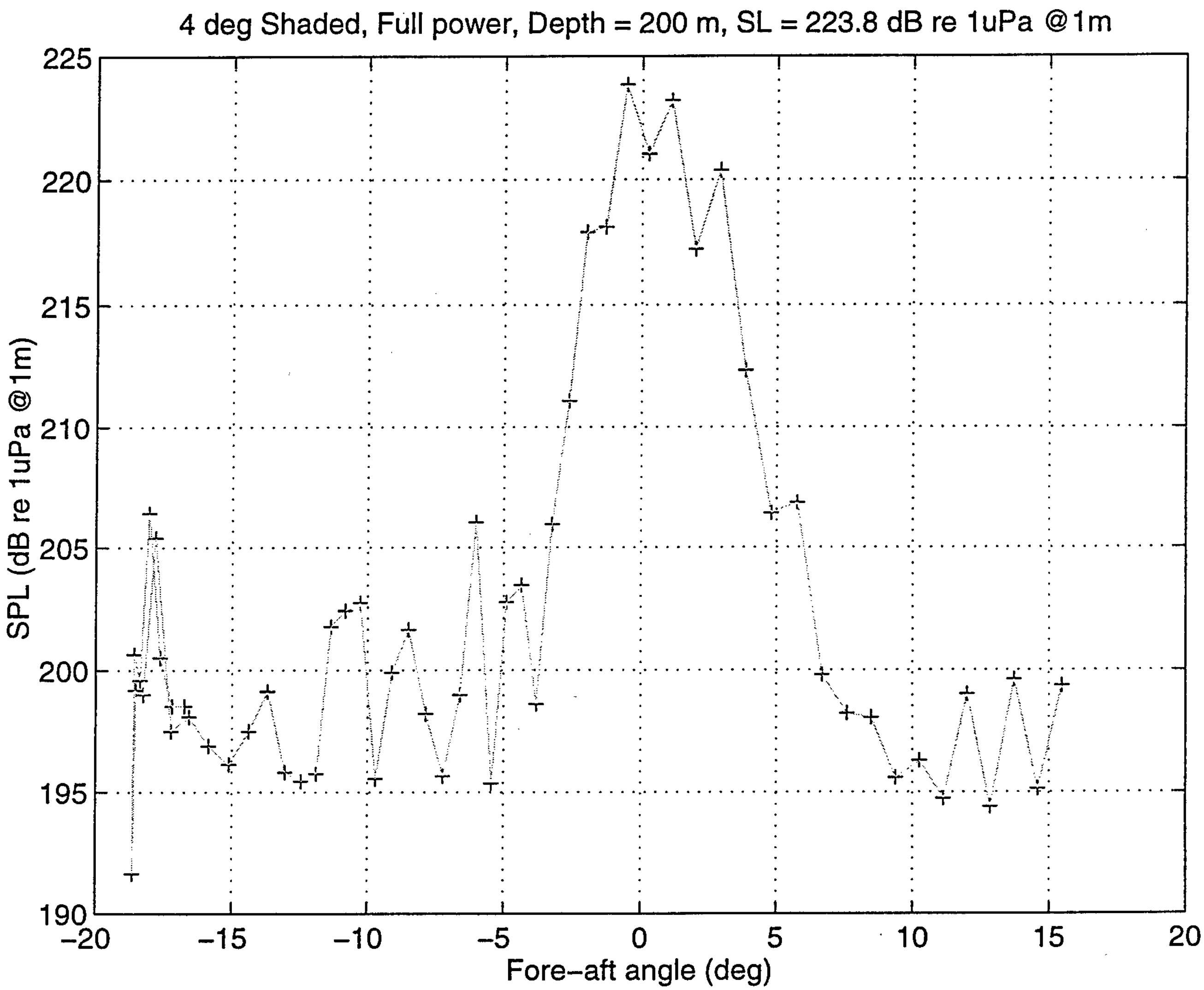

4 deg Shaded, Full power, Depth = 200 m, SL = 223.8 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
225
220
215
210
205
200
195
190
−20
−15
−10
−5
0
5
10
15
20
Fore−aft angle (deg)

Figure 12

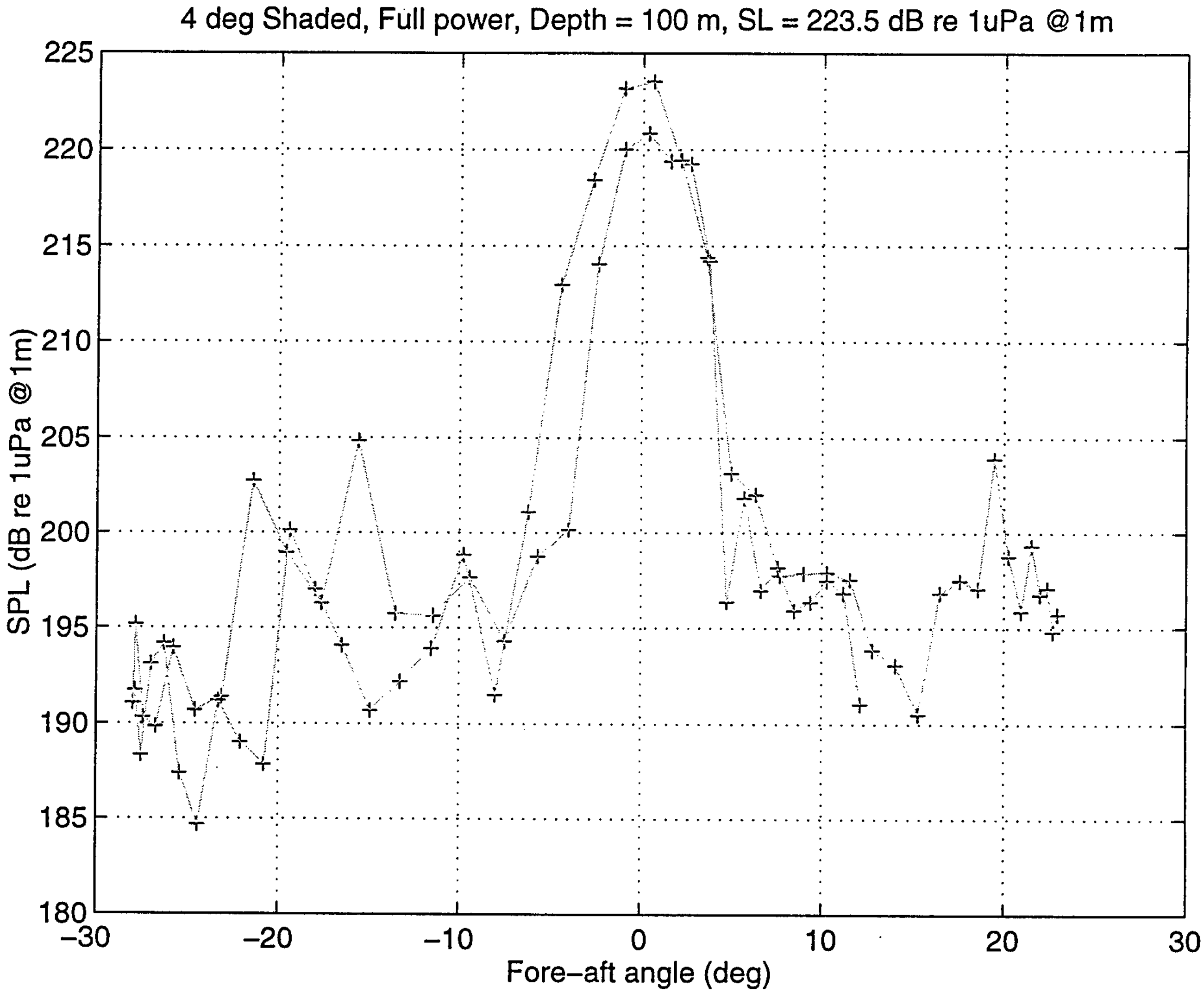

4 deg Shaded, Full power, Depth = 100 m, SL = 223.5 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
225
220
215
210
205
200
195
190
185
180
−30
−20
−10
0
10
20
30
Fore−aft angle (deg)

Figure 13

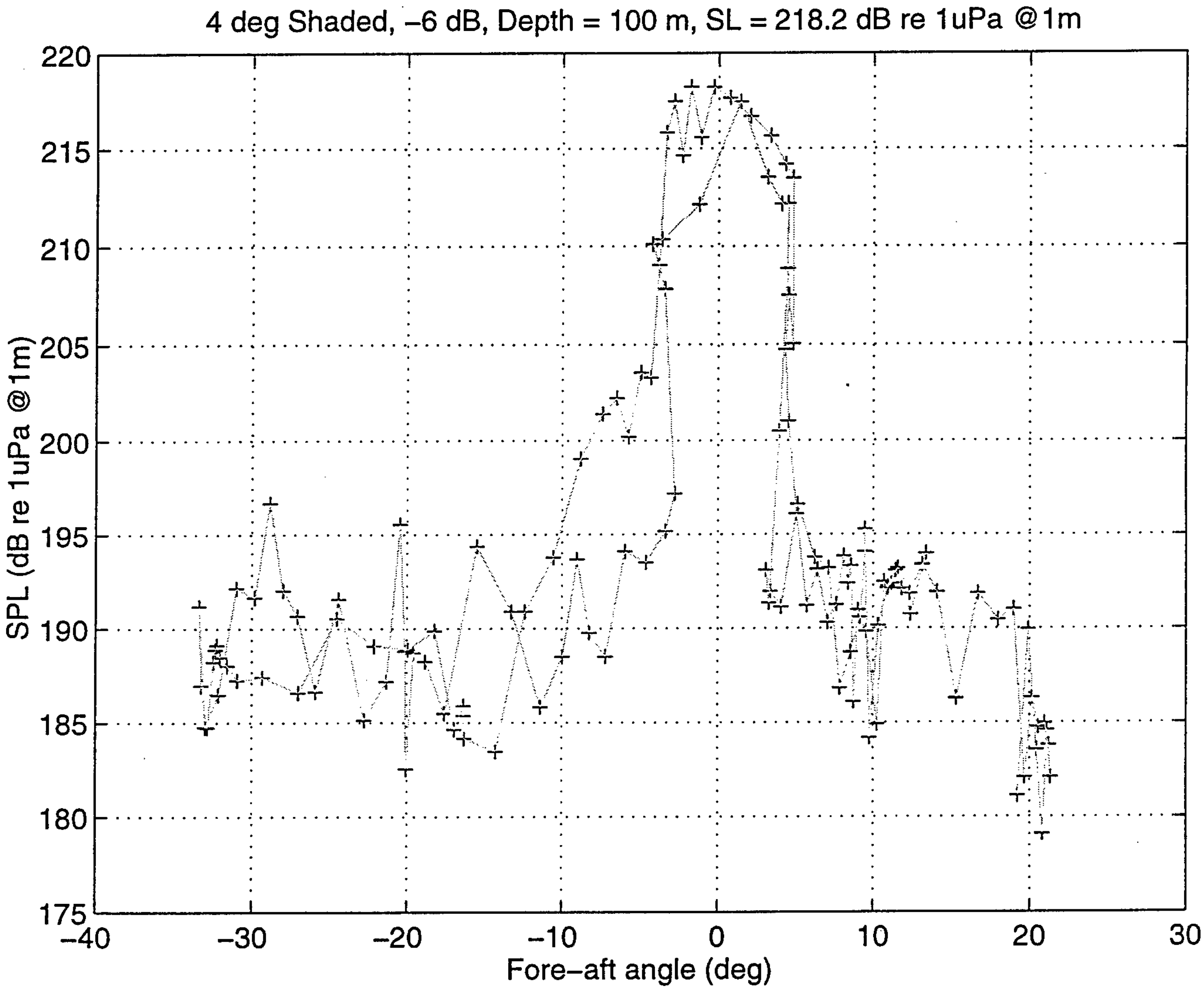

4 deg Shaded, −6 dB, Depth = 100 m, SL = 218.2 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore−aft angle (deg)
220
215
210
205
200
195
190
185
180
175
−40
−30
−20
−10
0
10
20
30

Figure 14

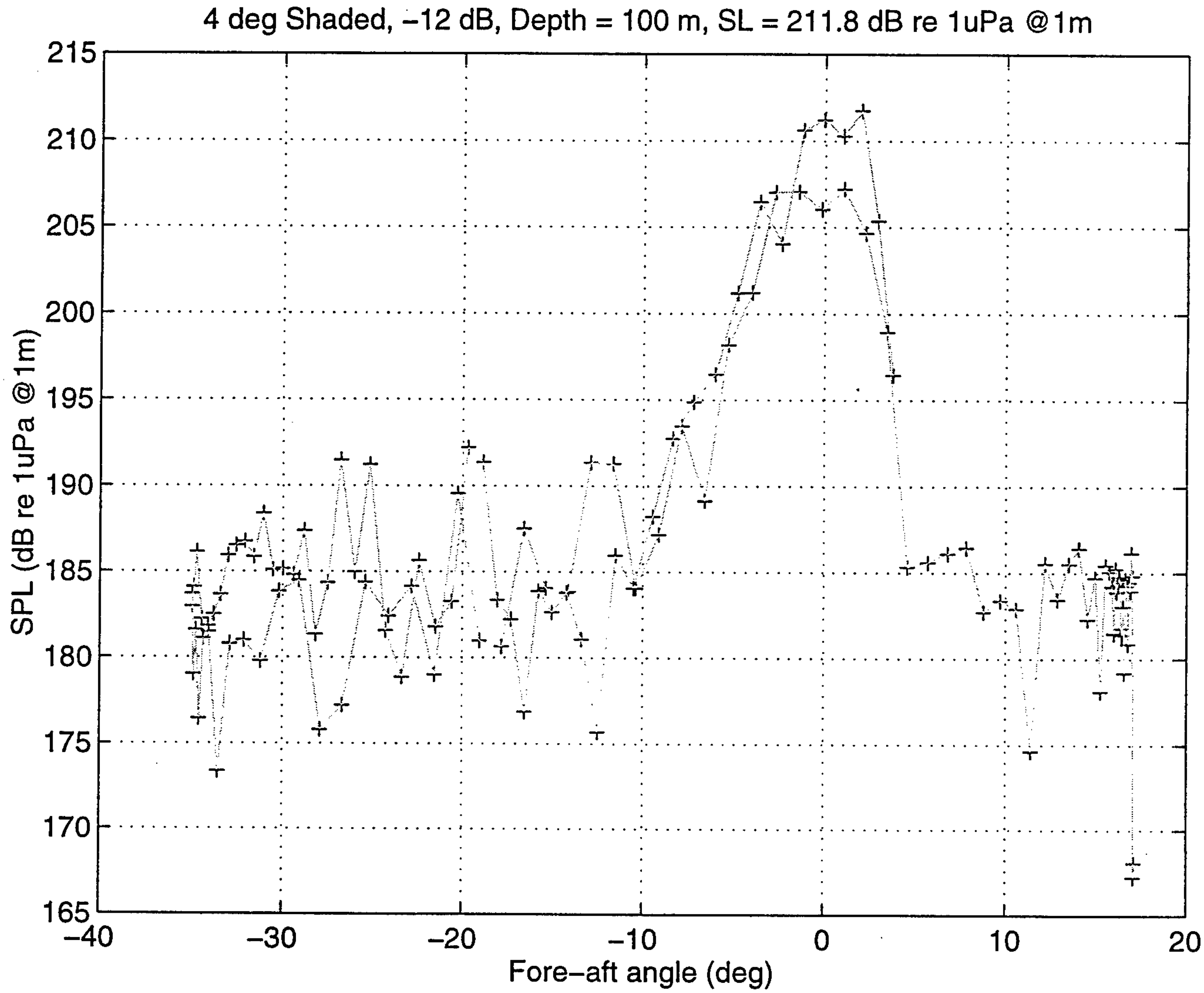
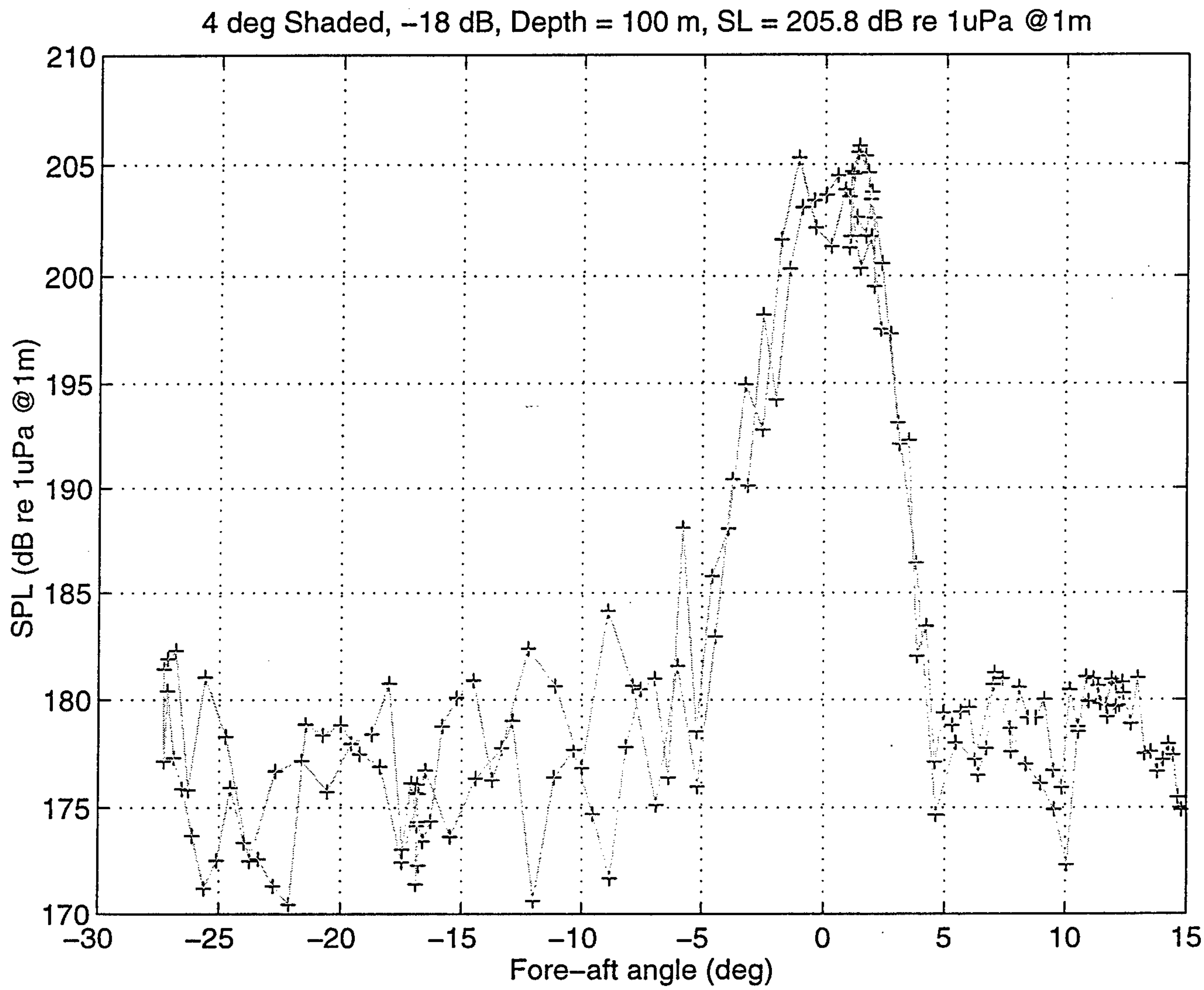

4 deg Shaded, –12 dB, Depth = 100 m, SL = 211.8 dB re 1uPa @1m
215
210
205
200
195
190
185
180
175
170
165
SPL (dB re 1uPa @1m)
–40
–30
–20
–10
0
10
20
Fore–aft angle (deg)

Figure 15



4 deg Shaded, –18 dB, Depth = 100 m, SL = 205.8 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
210
205
200
195
190
185
180
175
170
–30
–25
–20
–15
–10
–5
0
5
10
15
Fore–aft angle (deg)

Figure 16

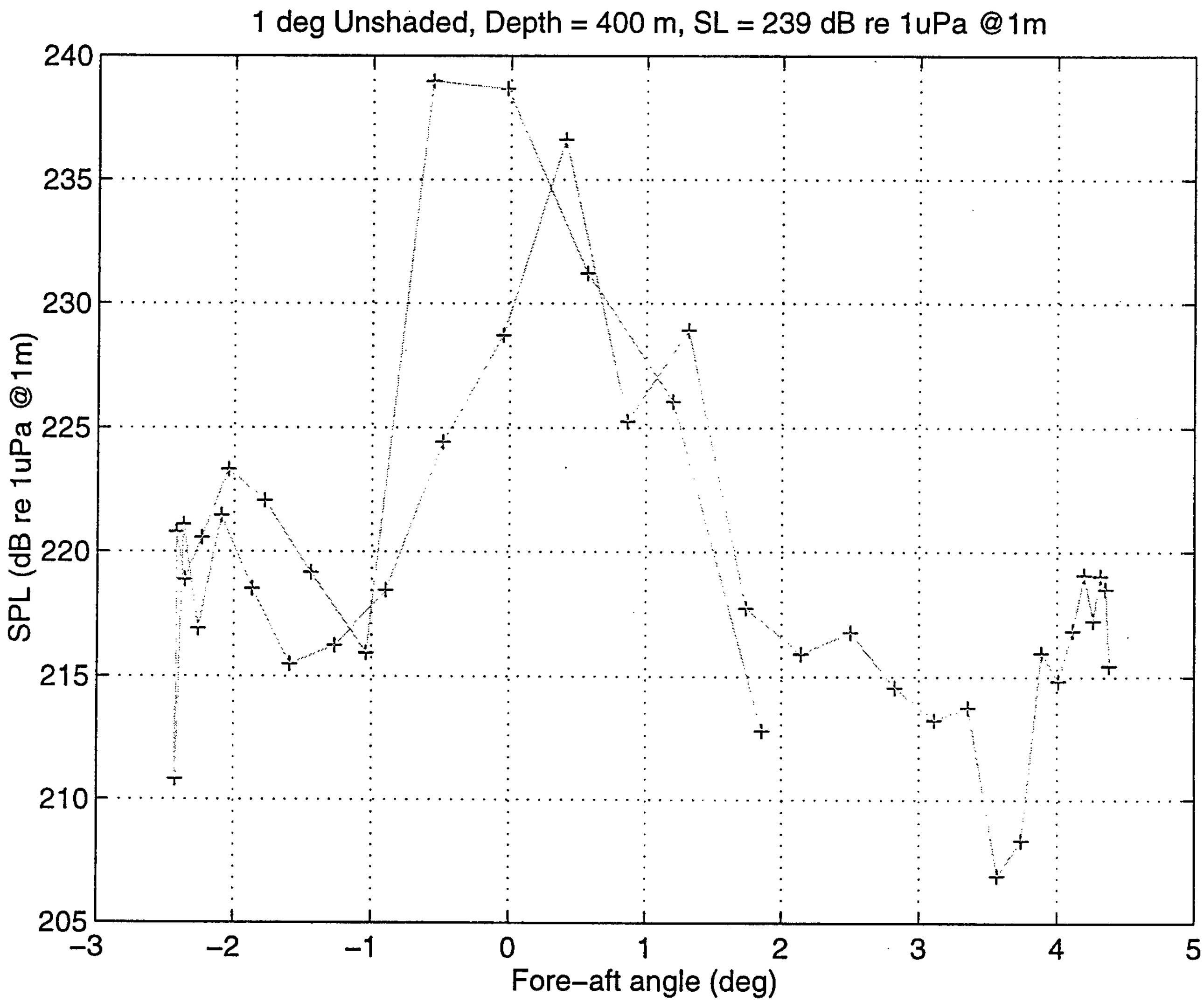

1 deg Unshaded, Depth = 400 m, SL = 239 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore–aft angle (deg)
240
235
230
225
220
215
210
205
–3
–2
–1
0
1
2
3
4
5

Figure 17

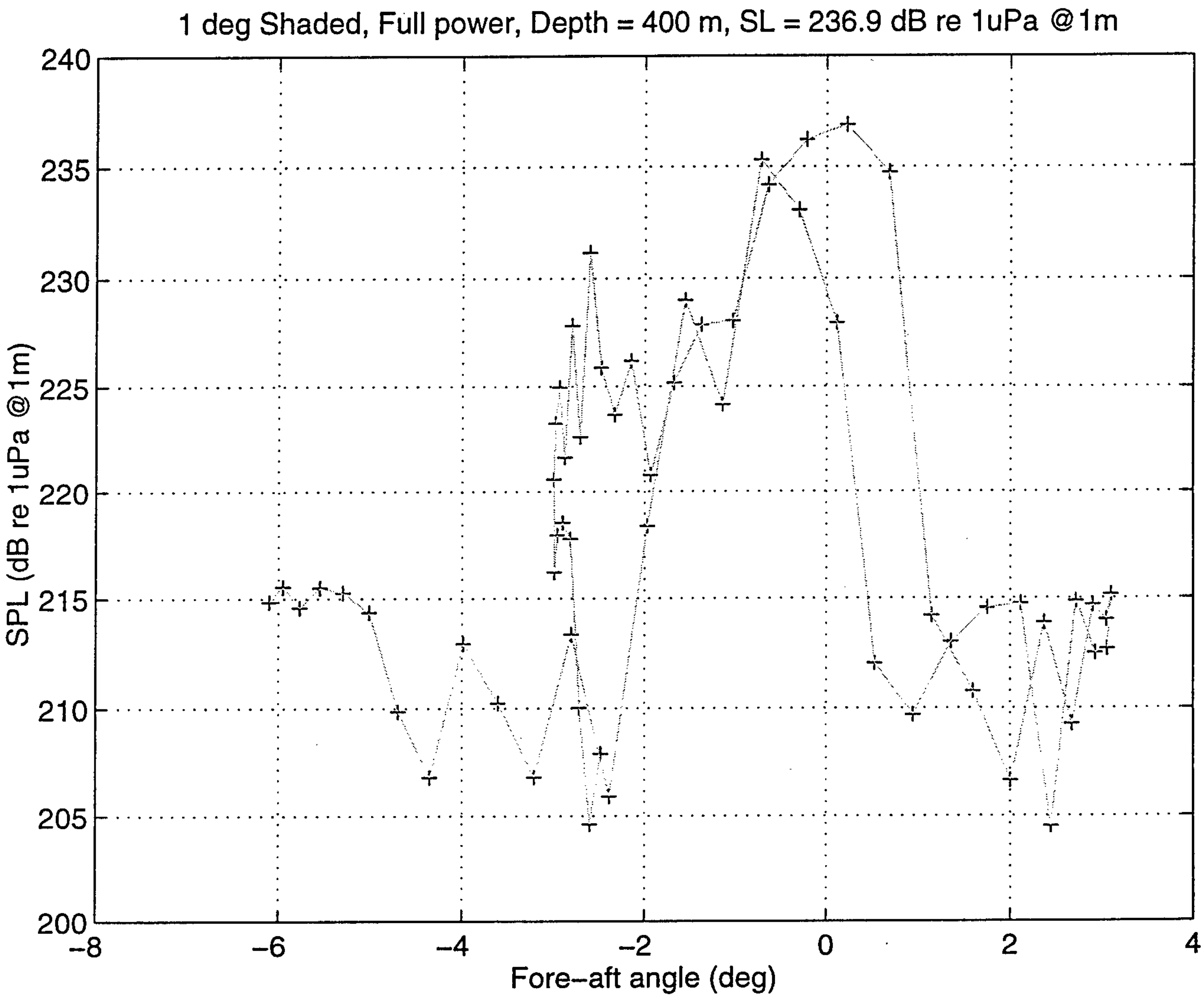

1 deg Shaded, Full power, Depth = 400 m, SL = 236.9 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore–aft angle (deg)
240
235
230
225
220
215
210
205
200
−8
−6
−4
−2
0
2
4

Figure 18

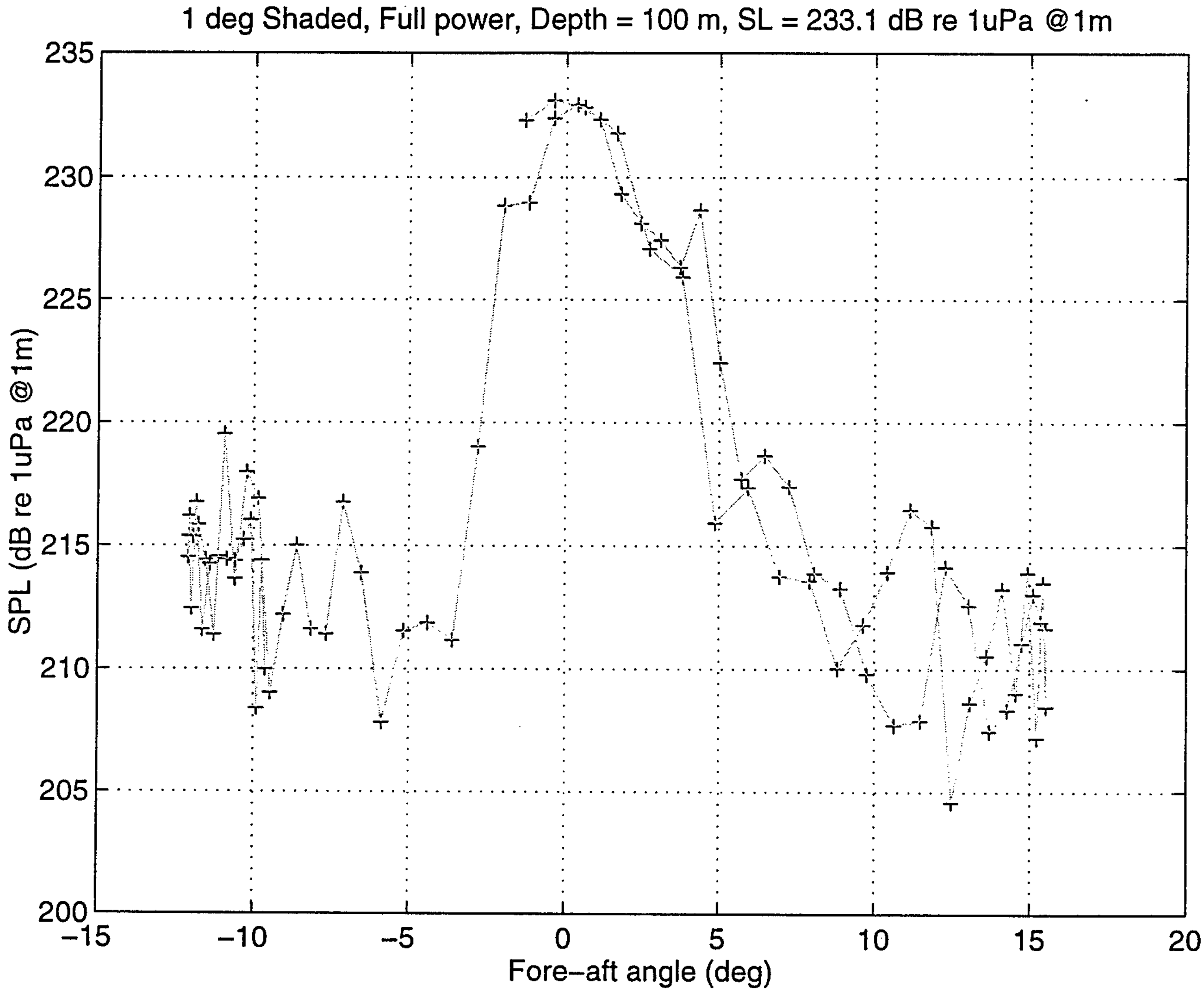
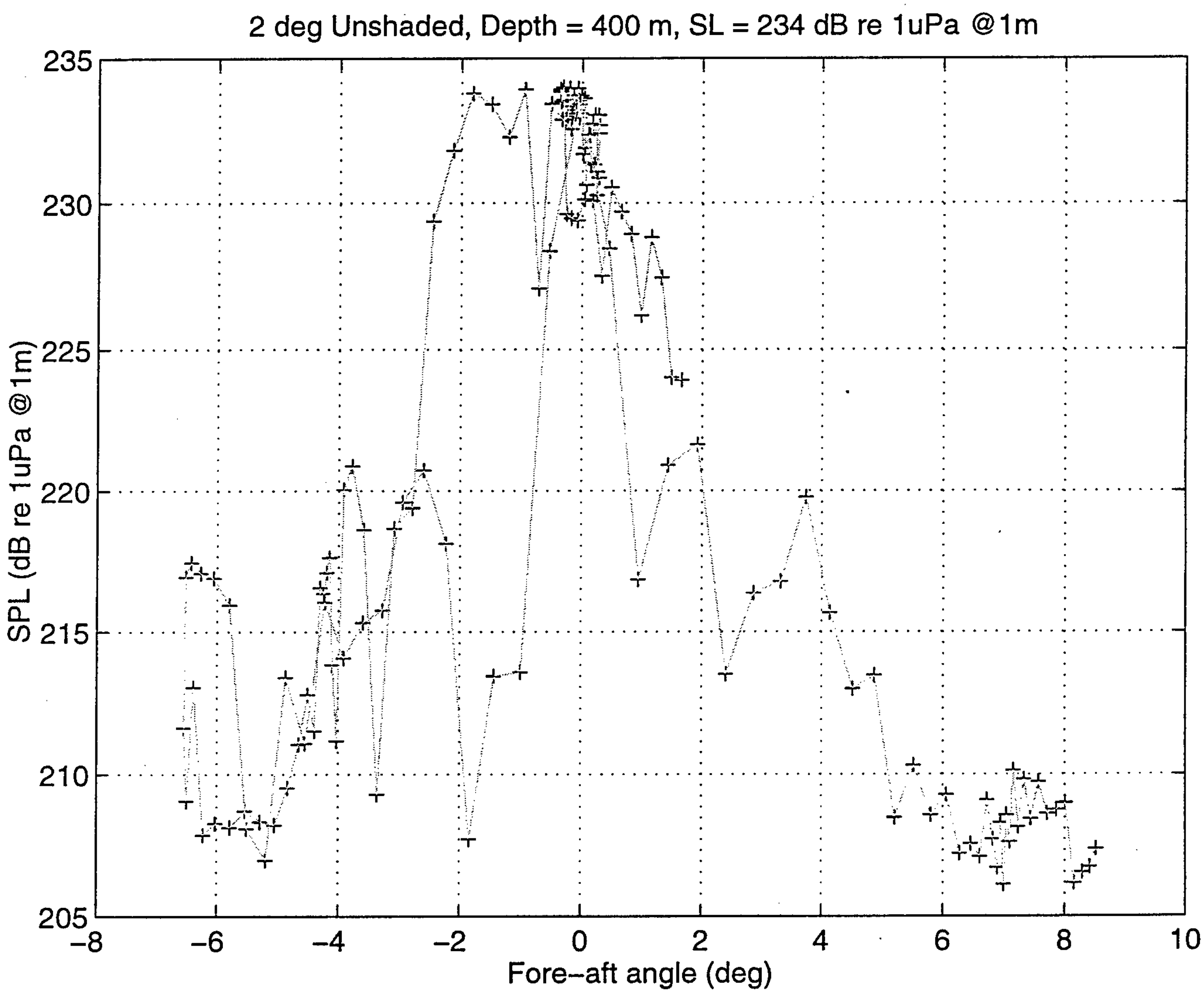

1 deg Shaded, Full power, Depth = 100 m, SL = 233.1 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore–aft angle (deg)
235
230
225
220
215
210
205
200
–15
–10
–5
0
5
10
15
20

Figure 19



2 deg Unshaded, Depth = 400 m, SL = 234 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
235
230
225
220
215
210
205
-8
-6
-4
-2
0
2
4
6
8
10
Fore-aft angle (deg)

Figure 20

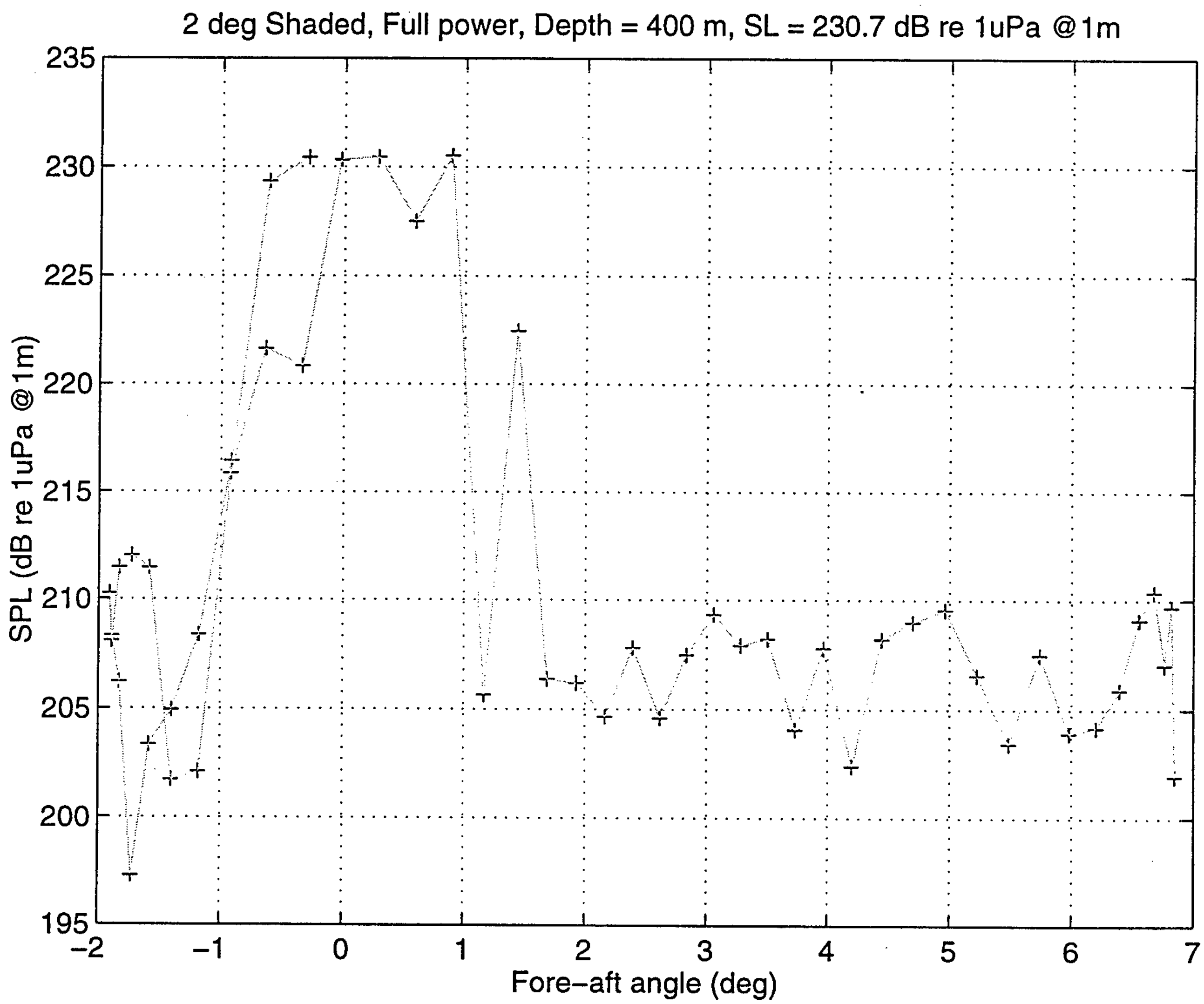
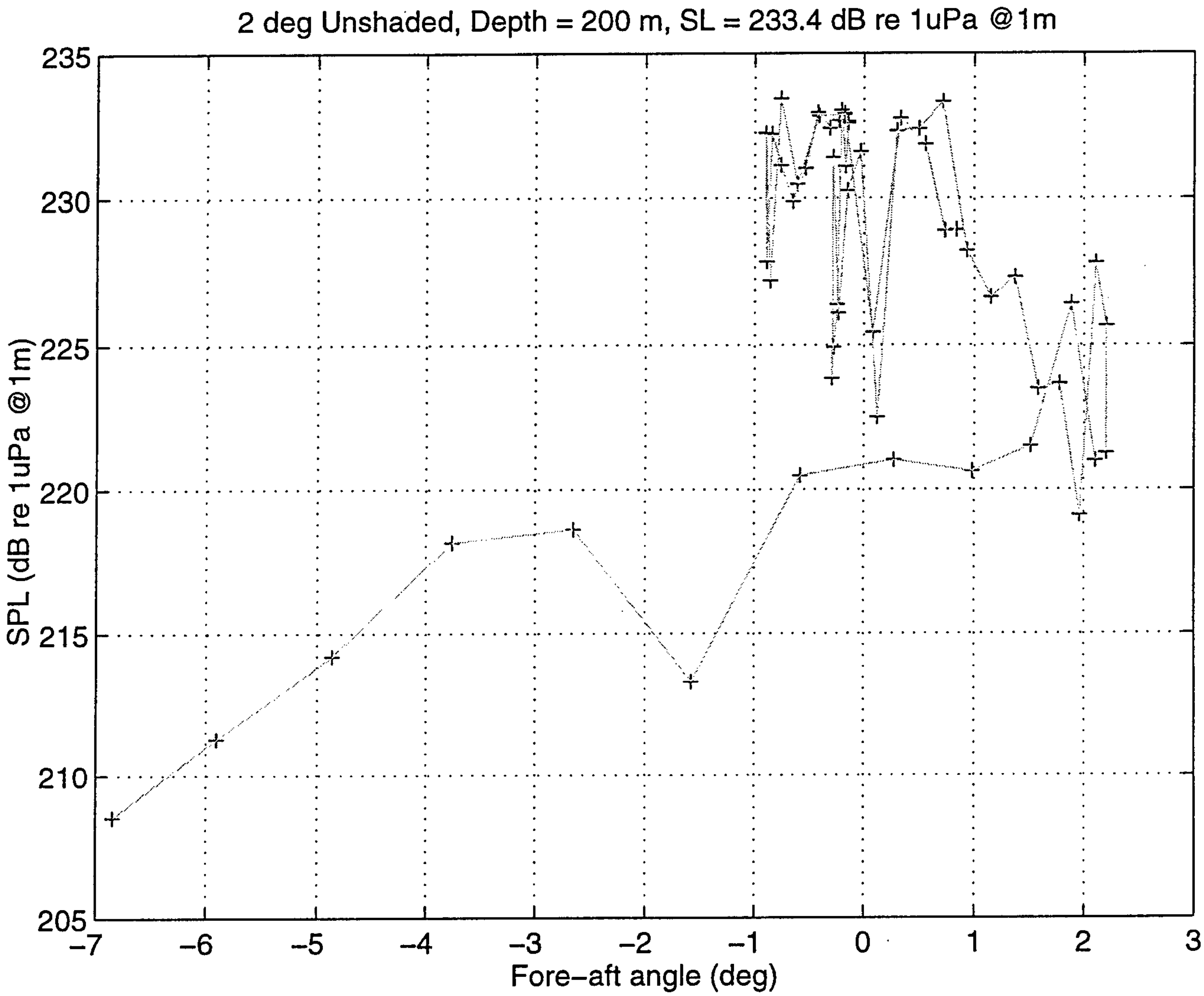

2 deg Shaded, Full power, Depth = 400 m, SL = 230.7 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
235
230
225
220
215
210
205
200
195
−2
−1
0
1
2
3
4
5
6
7
Fore−aft angle (deg)

Figure 21



2 deg Unshaded, Depth = 200 m, SL = 233.4 dB re 1uPa @1m
235
230
225
220
215
210
205
SPL (dB re 1uPa @1m)
−7
−6
−5
−4
−3
−2
−1
0
1
2
3
Fore−aft angle (deg)

Figure 22

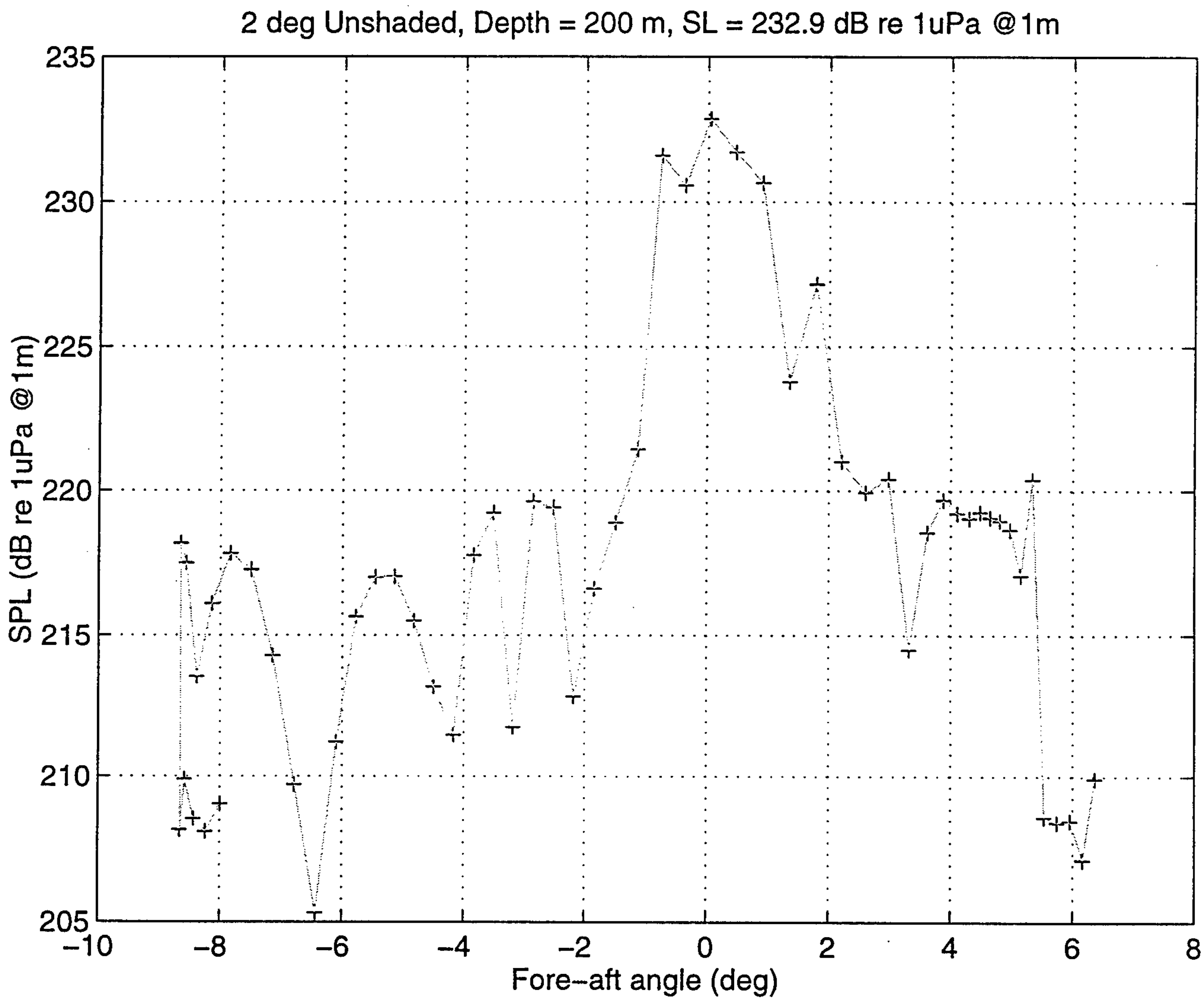

2 deg Unshaded, Depth = 200 m, SL = 232.9 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
235
230
225
220
215
210
205
−10
−8
−6
−4
−2
0
2
4
6
8
Fore−aft angle (deg)

Figure 23

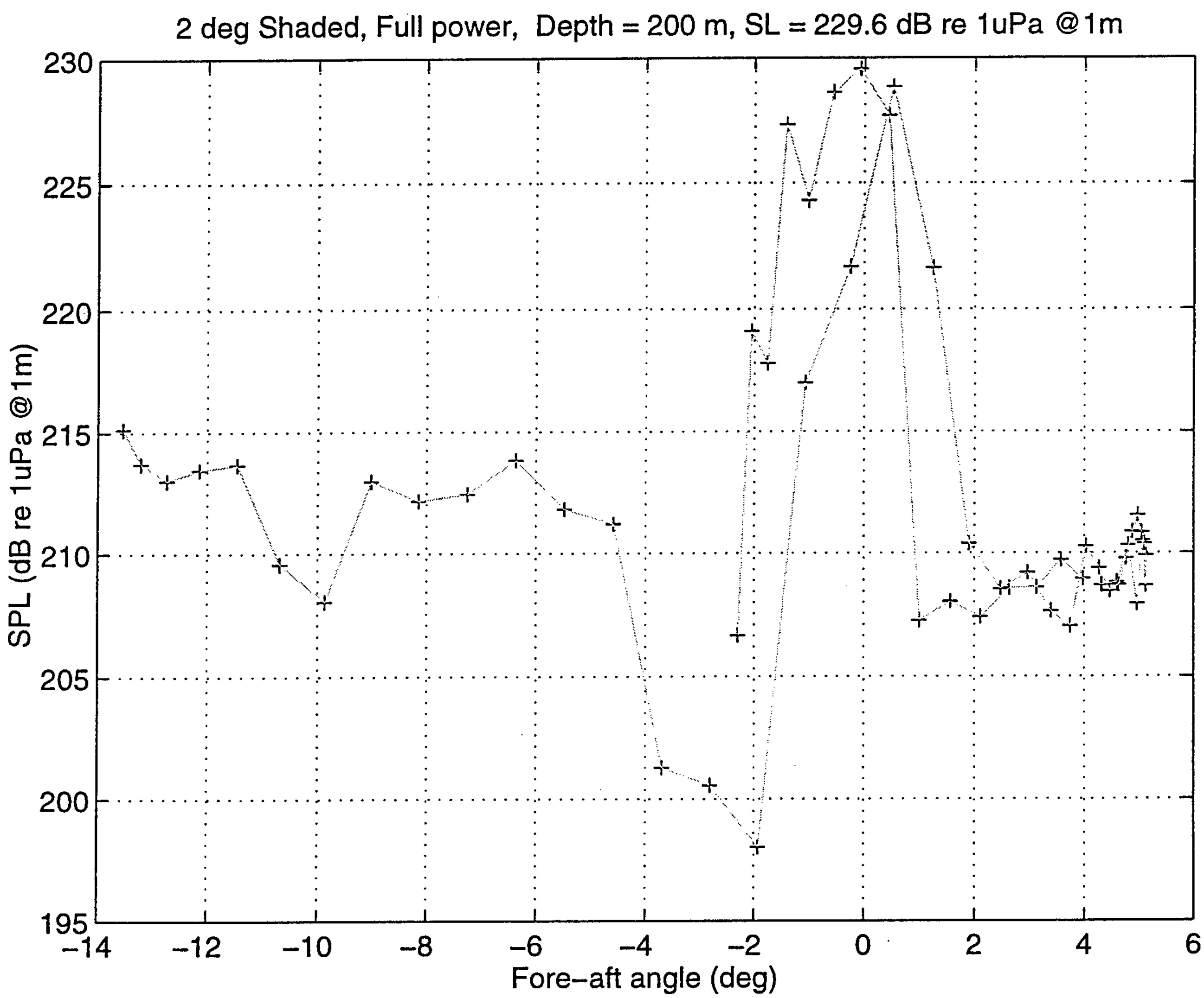
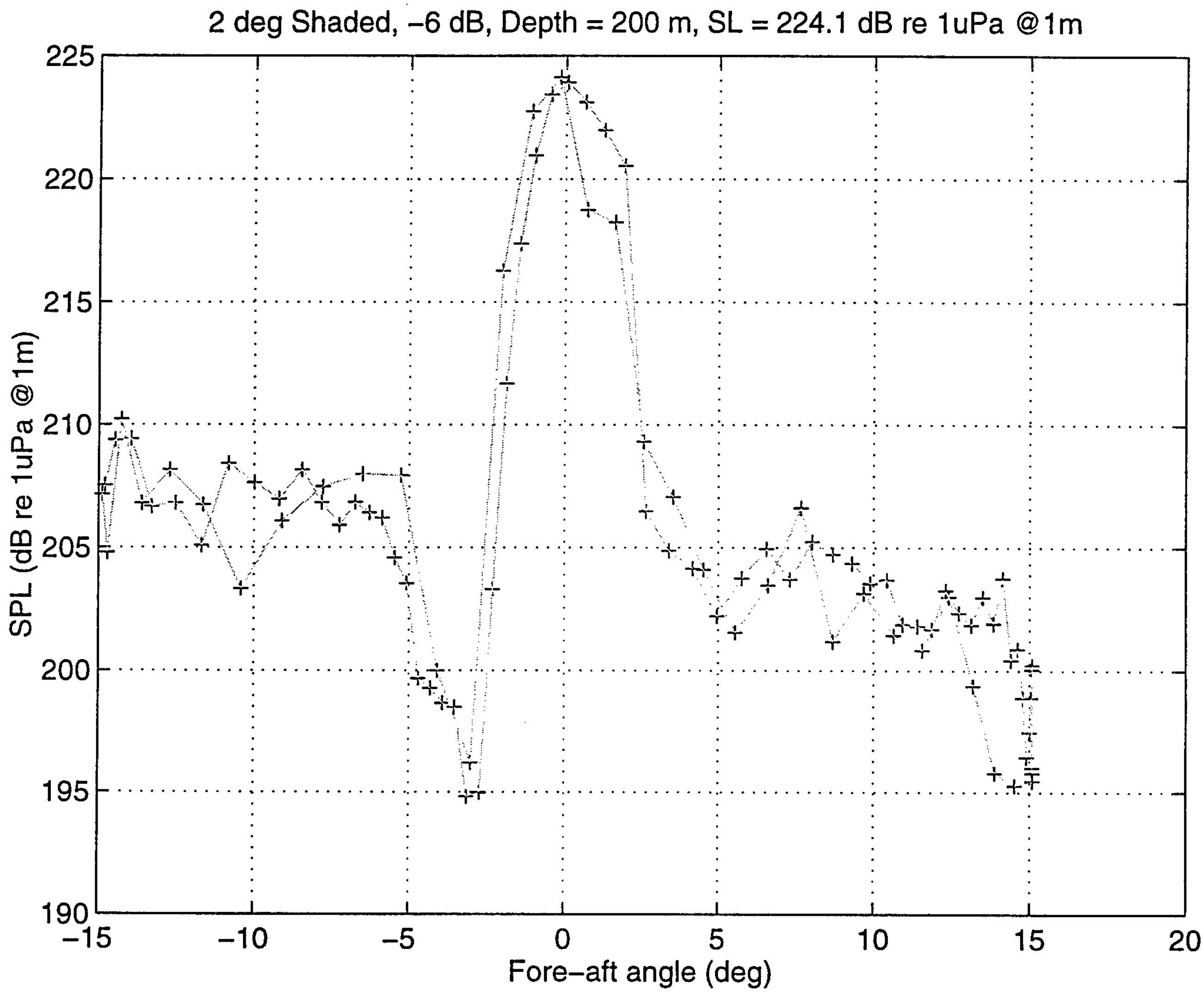

2 deg Shaded, Full power, Depth = 200 m, SL = 229.6 dB re 1uPa @1m
230
225
220
215
210
205
200
195
SPL (dB re 1uPa @1m)
−14
−12
−10
−8
−6
−4
−2
0
2
4
6
Fore−aft angle (deg)

Figure 24



2 deg Shaded, −6 dB, Depth = 200 m, SL = 224.1 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
225
220
215
210
205
200
195
190
−15
−10
−5
0
5
10
15
20
Fore−aft angle (deg)

Figure 25

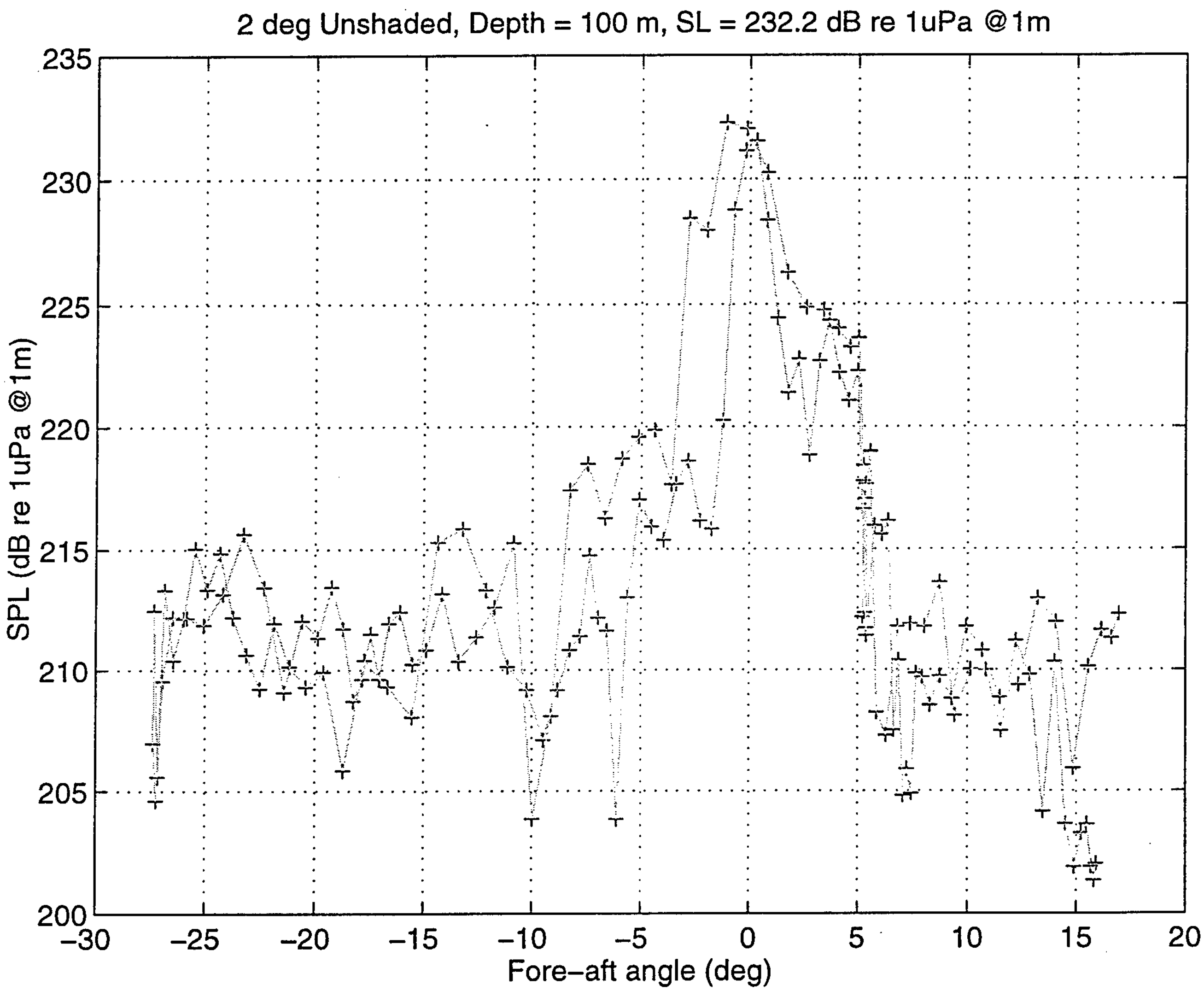

2 deg Unshaded, Depth = 100 m, SL = 232.2 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
235
230
225
220
215
210
205
200
−30
−25
−20
−15
−10
−5
0
5
10
15
20
Fore−aft angle (deg)

Figure 26

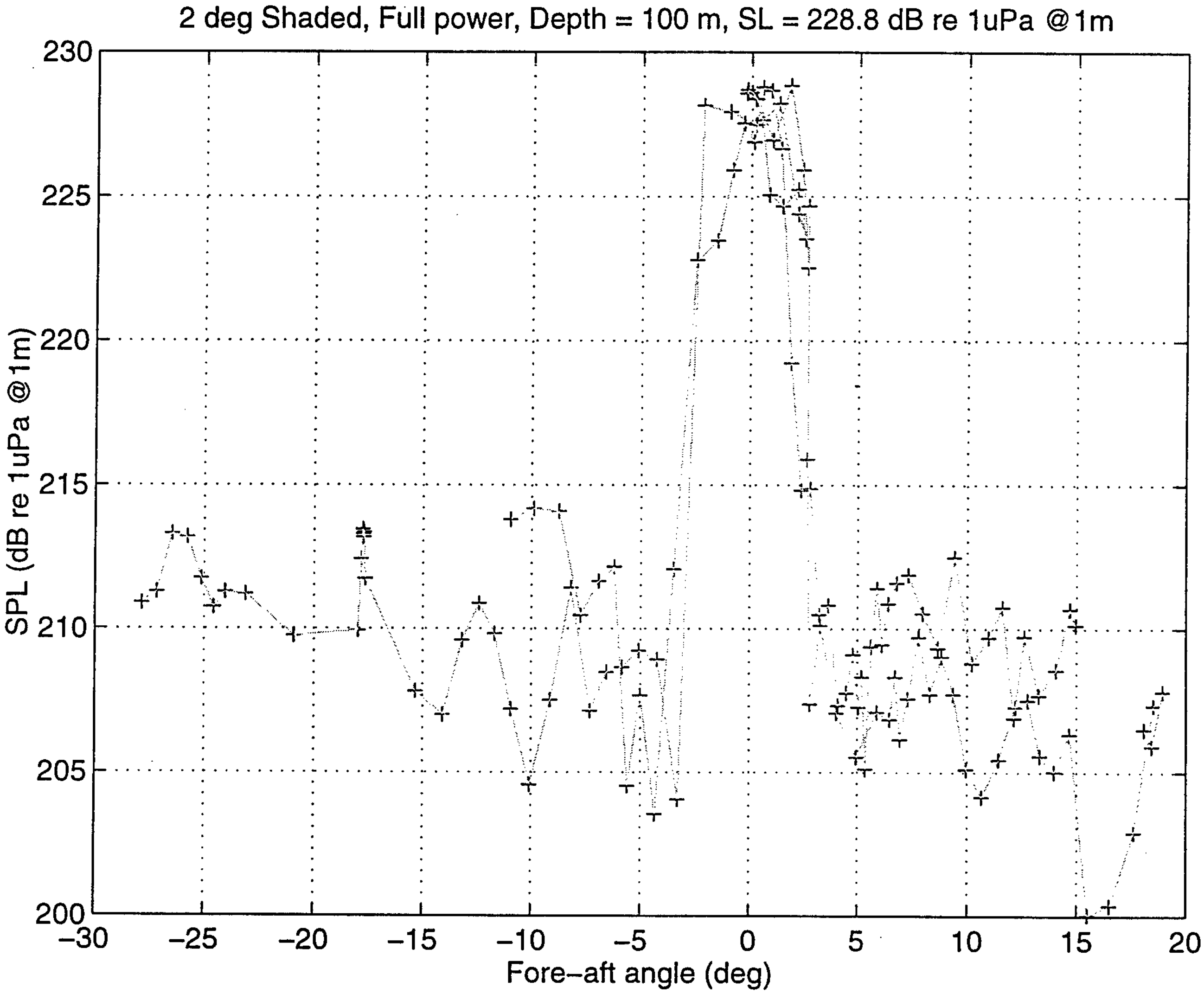

2 deg Shaded, Full power, Depth = 100 m, SL = 228.8 dB re 1uPa @1m
230
225
220
215
210
205
200
SPL (dB re 1uPa @1m)
−30
−25
−20
−15
−10
−5
0
5
10
15
20
Fore−aft angle (deg)

Figure 27

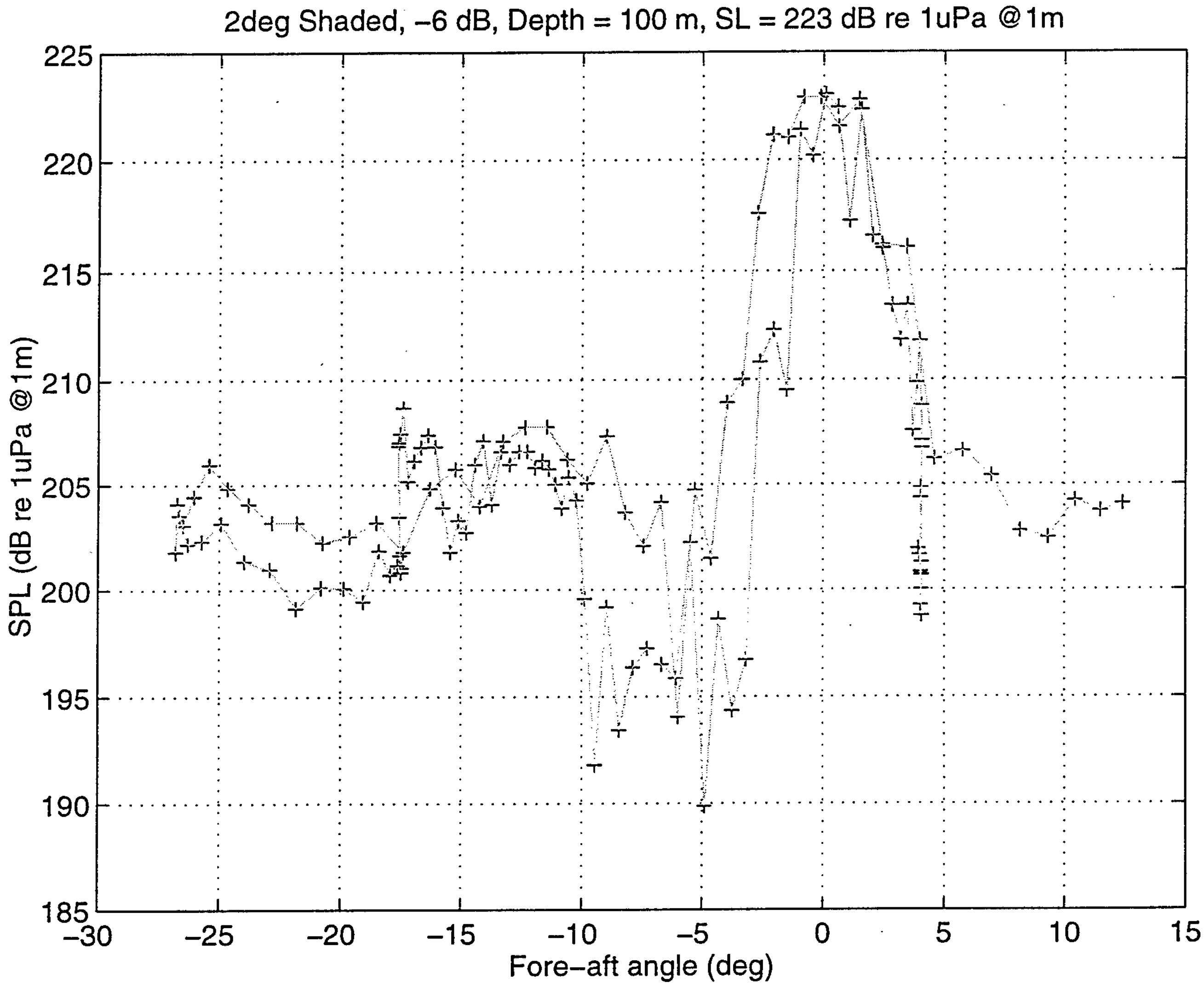

2deg Shaded, −6 dB, Depth = 100 m, SL = 223 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
225
220
215
210
205
200
195
190
185
−30
−25
−20
−15
−10
−5
0
5
10
15
Fore−aft angle (deg)

Figure 28

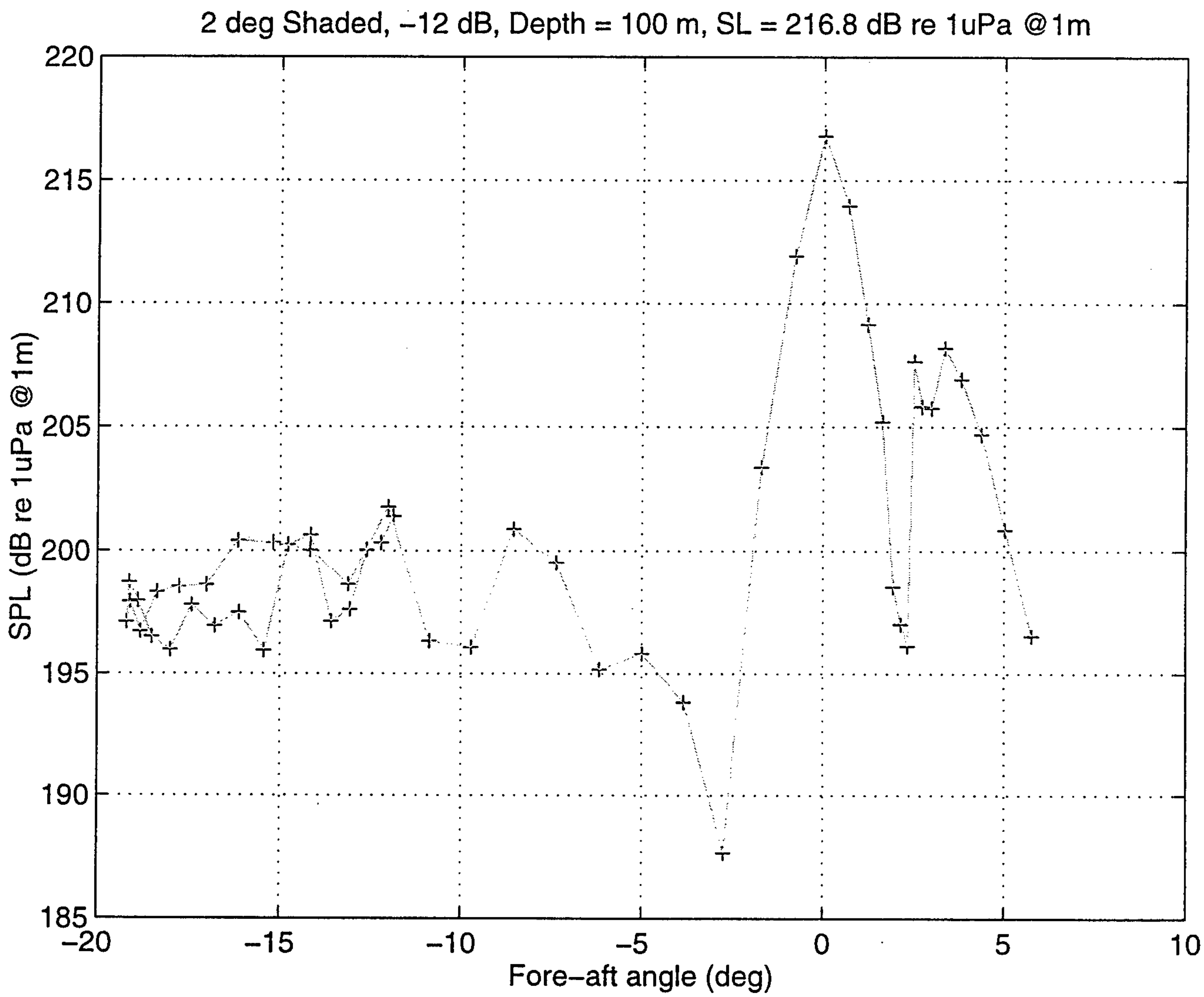
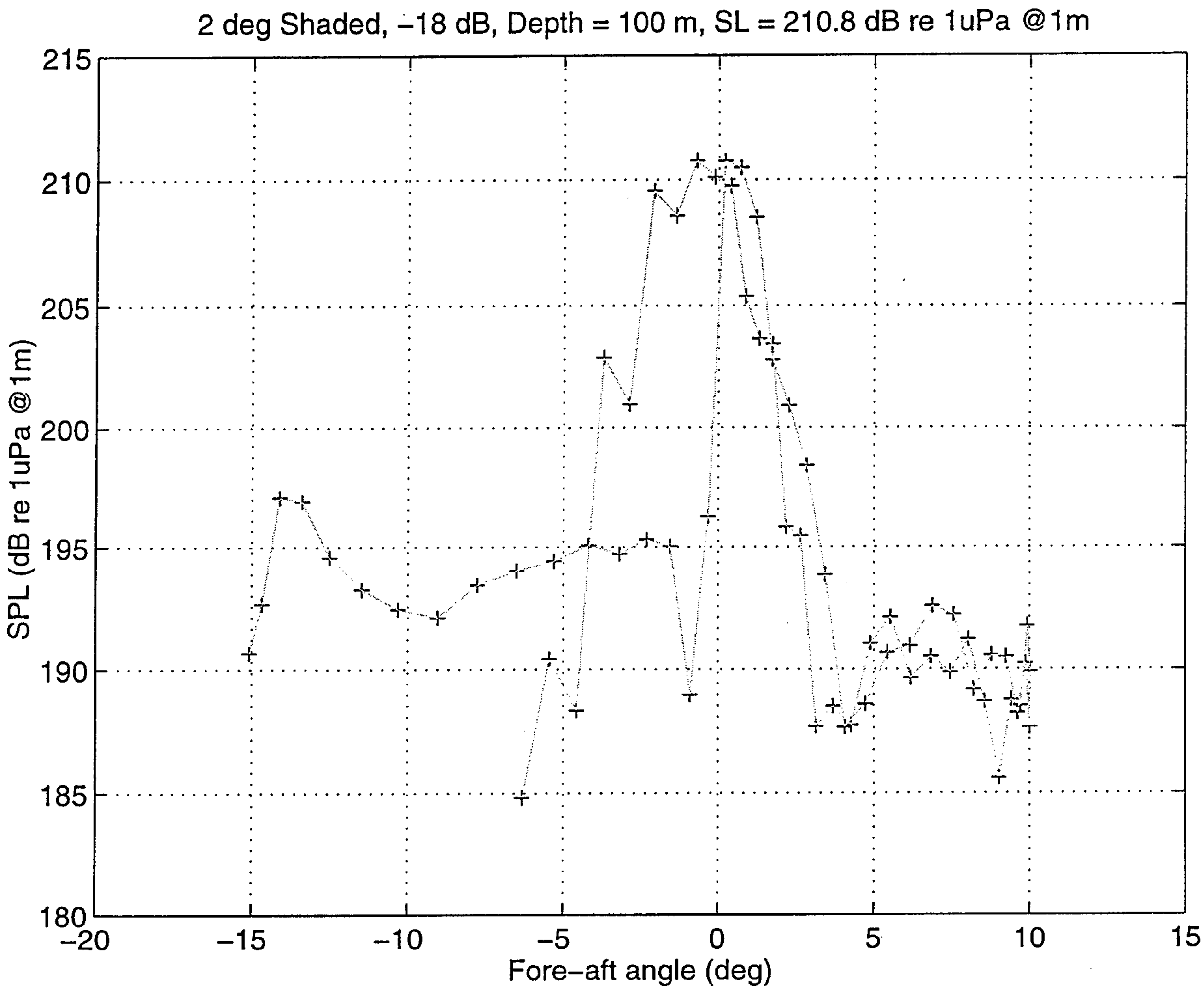

2 deg Shaded, -12 dB, Depth = 100 m, SL = 216.8 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore-aft angle (deg)
220
215
210
205
200
195
190
185
-20
-15
-10
-5
0
5
10

Figure 29



2 deg Shaded, -18 dB, Depth = 100 m, SL = 210.8 dB re 1uPa @1m
SPL (dB re 1uPa @1m)
Fore-aft angle (deg)
215
210
205
200
195
190
185
180
-20
-15
-10
-5
0
5
10
15

Figure 30

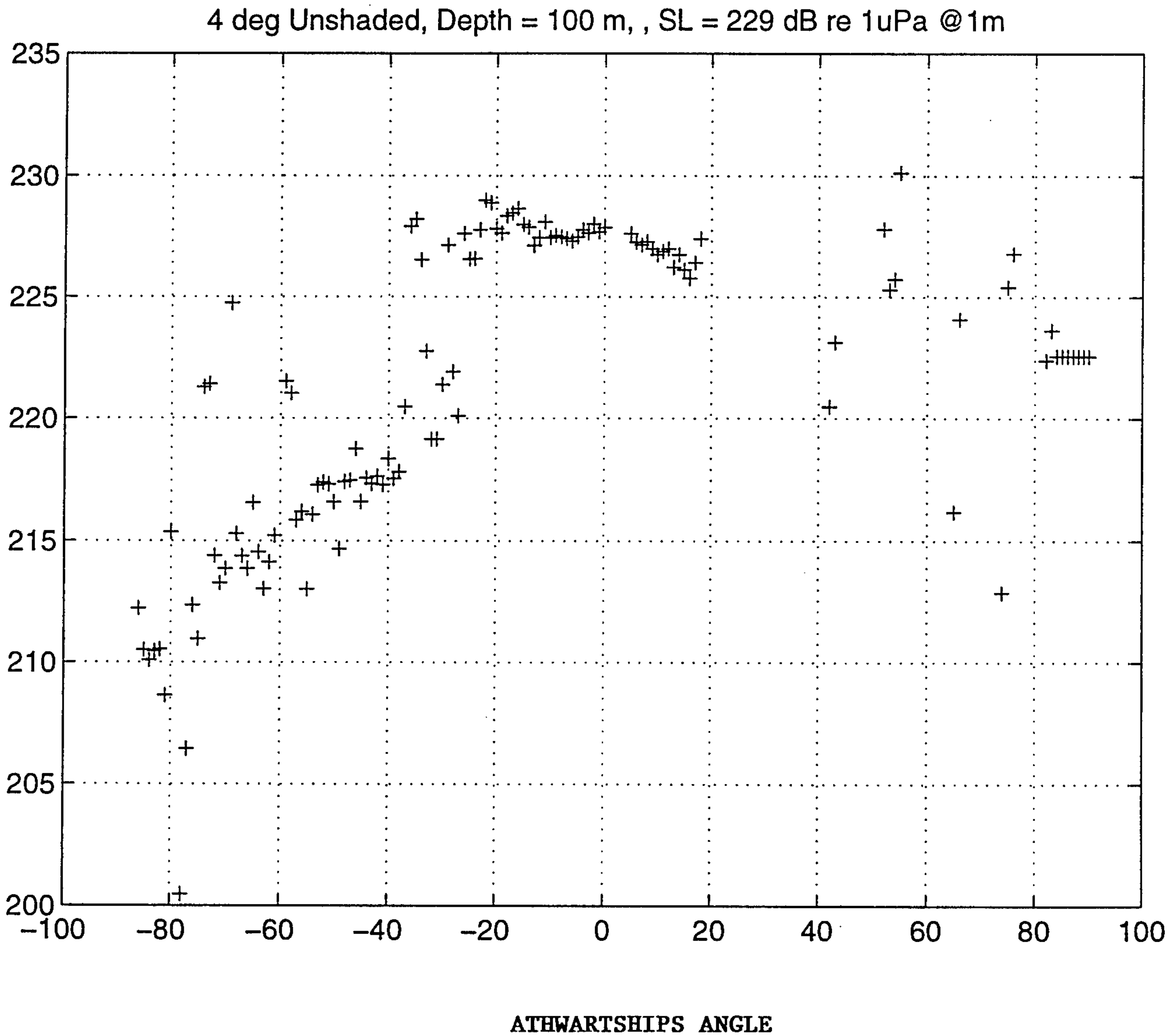

4 deg Unshaded, Depth = 100 m, , SL = 229 dB re 1uPa @1m
235
230
225
220
215
210
205
200
−100
−80
−60
−40
−20
0
20
40
60
80
100
ATHWARTSHIPS ANGLE

Figure 31

4 deg Unshaded, Depth = 100 m, , SL = 229 dB re 1uPa @1m (center=200)

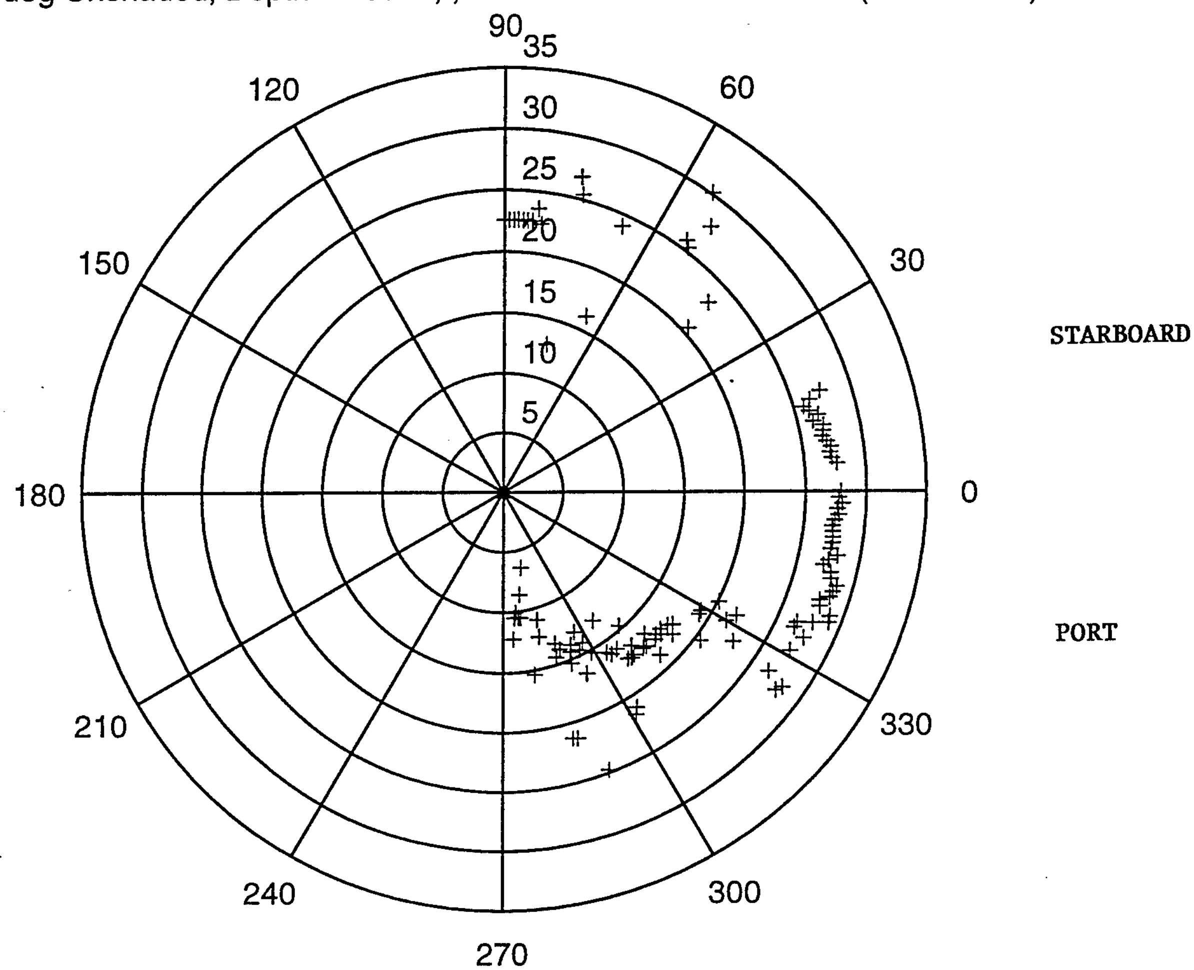


Figure 32

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